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ABSTRACT

Strategic Information Revelation and Revenue Sharing in an R&D Race

by Jos Jansen

Firms learn imperfectly about their cost of investment. We study how this information affects firms' incentives to invest in R&D by comparing investments and profits under public and private information. Revenue sharing between the winner and loser of the race, e.g. through licensing contracts, weakens the appropriability of the innovation's revenues, and creates free- rider effects. These free-rider effects not only soften R&D competition, but also affect the firms' incentives to acquire and reveal information. How much information firms eventually reveal, and consequently the information acquisition and innovation incentives, also depends on the verifiability of information.

Keywords: R&D, Competition, Revelation, Information Acquisition, Revenue Sharing
JEL Classification: D82, D83, L23, O31, O32

ZUSAMMENFASSUNG

Die strategische Preisgabe von Informationen und Einnahmeaufteilungen in einem F&E- Wettrennen

Unternehmen können ihre F&E-Investitionskosten nicht perfekt beobachten. Wir untersuchen, wie Informationen über diese Kosten die Investitionsanreize von Unternehmen beeinflusst. Zu diesem Zweck vergleichen wir das Investitionsniveau und die Gewinne bei öffentlich verfügbaren Informationen mit den entsprechenden Werten bei privaten Informationen. Eine Aufteilung der Einnahmen zwischen dem Gewinner und dem Verlierer des Rennens, beispielsweise durch Lizenzverträge, schwächt die Möglichkeiten, sich die Einnahmen aus der Innovation anzueignen und schafft Trittbrettfahrereffekte. Die Trittbrettfahrereffekte mildern nicht nur den F&E-Wettbewerb sondern beeinflussen auch die Anreize des Unternehmens, Informationen zu beschaffen und offenzulegen. Die Menge der Informationen die sich die Unternehmen beschaffen, die letztendlich von den Unternehmen preisgeben werden und die Innovationsanreize hängen darüber hinaus von der Überprüfbarkeit der Informationen ab.

1 Introduction

Innovative firms that invest in research and development (R&D) create new information in an industry. Firms in an R&D race actively manage this information. It is well-known that firms are only willing to reveal the contents of their innovation if this innovation is sufficiently protected.[1] Firms do not only manage information about the contents of their innovation, but also strategically reveal and conceal information about their relative efficiency to affect competition in R&D. For example announcements by firms in high-tech industries, such as the biotech and the software industry, about intermediate successes are common in practice. While most literature on R&D competition focuses on incentives for revelation of the innovation's contents, this paper analyzes incentives for the acquisition and revelation of the innovators' costs of investment.

The incentives to reveal intermediate information are determined by the effect of this information on the firms' incentives to invest in R&D. We study these incentive effects by comparing investments and profits under public and private information.

We distinguish two conflicting effects of information about a firm's R&D efficiency on competition by the firm's rivals. First there is a "strategic effect". A firm that has a leading position in an R&D race obtains a strategic advantage, which weakens its rivals' incentive to invest in obtaining the innovation. Therefore good news about one firm's relative expected cost of investment reveals that the firm will be an aggressive R&D investor, which discourages its rivals. This effect is analyzed extensively in the literature on dynamic R&D competition, see e.g. Grossman and Shapiro (1987), and Harris and Vickers (1987).

The second effect, which conflicts with the strategic effect, is the "informational effect". Good news about one firm's efficiency does not only reveal information about the relative efficiency of the firm, but can also reveal information about the absolute cost of investment. When firms apply similar R&D technologies to make their innovation, their costs of investments are correlated. In that case, good intermediate news for one firm makes its rivals

[1] For overviews of the basic issues, see e.g. Scotchmer (1991), and Ordover (1991).

more optimistic about their opportunities in the R&D race, which intensifies competition.[2] Choi (1991) and Malueg and Tsutsui (1996) analyze the R&D investments that result from the trade-off between the strategic and informational effects. We focus in this paper on the informational effect of intermediate information, by assuming perfect positive correlation between the firms' costs of investment. This enables us to ignore the incentive effects of revealing the contents of the firms' innovation, since this information is the same for the firms in the race.

Besides the incentive effects of intermediate information, we study the effects of changes in the appropriability of the innovation's revenues on the firms' investment incentives. Most literature on R&D races focuses on investors' incentives in a "winner-take-all" race. This is, however, an extreme setting that needs not be realistic. We therefore study an R&D race in which the winner does not necessarily take all the innovation's revenues. In particular we introduce a fixed share of the winner's revenue that spills over to the loser of the race. Such a revenue share can be implemented by two-part licencing contracts with a royalty rate and a fixed fee, as argued in Shapiro (1985). The royalty rate keeps total the industry's revenue constant, while the size of the fixed fee determines the share of the revenue that the winner of the race can appropriate.[3] Revenue sharing introduces free-rider effects to the analysis that softens the R&D rivalry. These free-rider effects interact in an interesting way with the informational and strategic effects.

The effects for incentives of racing firms after the relaxation of the winner-take-all assumption are studied in La Manna *et al.* (1989), Denicolò (1996), Moldovanu and Sela (2000), and Palomino and Sákovics (2000). These pa-

[2] Illustrations of the informational effect are given for the race for cold superconductivity, and biotech. Choi (1991) gives an example of the 1986 breakthrough in cold superconductivity by IBM. This intermediate success increased the intensity of the race for superconductivity. In the biotech industry Austen (1993) observes that an intermediate success by one biotech firm leads to an increase in valuation of other firms in the industry.

[3] We make the extreme assumption that total industry revenues after licensing remains constant to focus on free-rider effects that softens R&D competition. More realistic incomplete licensing contracts (e.g. contracts with non-negative fees, or contracts without royalty rate) would introduce countervailing product market competition effects that distort investment incentives. We ignore product market competition effects to keep the analysis tractable.

pers seriously question the efficiency of races where the winner takes all, and analyze the optimal allocation of prizes among the contestants of the race. Our paper also finds that a positive revenue share softens investment competition among firms, but in addition we study the consequences of revenue sharing for information revelation and acquisition incentives.

After the effects of intermediate information on investors' incentives are established, we endogenize the firms' intermediate information in two ways. First information is endogenous because firms can choose what information they reveal. That is, the revelation of information is not exogenous, but a strategic choice of the firms. Whether firms compete in R&D under public or private information is now determined by the revelation strategies of the firms. In particular we analyze how the firms' incentives to reveal information depend on the verifiability of this information and on the appropriability of revenues. When information is non-verifiable, firms never completely reveal their information, while there is an equilibrium in which they completely conceal information. This result holds regardless of how firms share revenues. These results are reversed for extreme revenue shares, however, when information is verifiable. Firms cannot credibly conceal any verifiable information, and will therefore fully disclose. For intermediate revenue shares there is no equilibrium in which firms completely reveal their information.

The second way in which we endogenize the firms' information is by assuming that each firm invests in costly information acquisition. Firms' expectations in the R&D race depend both on the amount of information that is revealed by their rivals, and on the amount of information that each firm acquires. The incentives to acquire information depend on the appropriability of both the acquired information, and the innovation's revenues. When the acquired information is public, firms have a low incentive to invest in information acquisition, because they prefer to free ride on their rival's information acquisition investments. And when only part of the revenues from innovation are appropriated by a firm, both negative as well as positive externalities on information acquisition incentives exist between firms. The negative effect is due to the erosion of expected revenues from a firm's own information acquisition investments. This is a free-rider effect. The positive externality of revenue sharing is present when the firms' acquired information is public. The externality is caused by the fact that the information generated by one firm affects beliefs and consequently expected revenues of the rival firm. Since part of these revenues spill over, firms have a bigger incentive to invest in information acquisition.

Problems of strategic information revelation in R&D races are studied in e.g. Bhattacharya *et al.* (1990, 1992), and Katsoulacos and Ulph (1998). These papers are concerned with information revelation about the contents of an intermediate innovation, where this information is not actively acquired by the firms. These papers therefore put more emphasis on the strategic effect of information revelation. The literature on information sharing in oligopoly studies the incentives of competing firm to share information without spillovers of contents, see e.g. Novshek and Sonnenschein (1982), Fried (1984), and Creane (1995) for papers with information acquisition.[4] But this literature mostly assumes that firms can commit *ex ante* whether to reveal information or not. This is a strong assumption that need not always be realistic. In fact, Ziv (1993) shows that the scope for information sharing is drastically reduced when firms cannot commit *ex ante* and information is non-verifiable. We follow the same modelling approach as in the paper by Ziv.

The interaction between information acquisition and subsequent competition is studied in Hendricks and Kovenock (1989), Choi (1991), Malueg and Tsutsui (1997), Cyert and Kumar (1998), Dewatripont *et al.* (1999) and Cripps *et al.* (2000). These papers study models in which firms learn about their project's characteristics while they invest in it. In the former four papers the acquired information is publicly observable, i.e. firms learn from each other's experience without cost. We show in this paper that firms have incentives to misrepresent their intermediate information to affect future competition. Dewatripont *et al.* (1999) give sufficient conditions under which a manager's incentives for information acquisition investments are affected by an additional signal about his project. We perform a similar exercise for signals that are generated by a firm's rival. We extend the anal-

[4] For a recent survey on information sharing in oligopoly, see e.g. Raith (1996).

ysis by introducing competition in information acquisition, and by studying the effects of imperfect appropriability of the inventor's prize. Cripps *et al.* (2000) compares experimenters' incentives for information acquisition under public and private signals, and focuses on the experimentation dynamics. While some incentives effects are related to ours, we add profit comparisons, and analyze the strategic effects of revenue sharing. In particular we show that firms' expected profits can be increased by relaxing the winner-takes-all assumption.

The paper is organized as follows. In the next section we describe the basic model. In section 3 the total profit maximizing investments and profits are characterized. This efficient outcome serves as a benchmark. Section 4 analyzes the effects of introducing competition in the winner-take-all race. We compare the outcome of the race with public signals with the outcome with private signals. In section 5 we analyze how the equilibrium investments and profits change when the winner of the race shares part of his revenues with the loser. The sixth section discusses how much information is revealed, and consequently what investments are chosen, when firms reveal information strategically. Section 7 discusses strategic information acquisition incentives in the R&D race, and the last section concludes the paper. All proofs are relegated to the Appendix.

2 The Basic Model

We consider an industry in which two firms compete to obtain an innovation. Firms have identical costs of investments, i.e. costs are perfectly positively correlated. In the first stage nature chooses the firms' costs of investment and sends a signal about it to the firms. In the second stage the firms actually invest in R&D to obtain the innovation.[5]

At the beginning of the race firms do not know their cost of investment. This cost is summarized by the parameter θ, which is either low, $\theta = \underline{\theta}$, or high, $\theta = \overline{\theta}$ with $0 < \underline{\theta} < \overline{\theta}$. Firms have low (resp. high) costs of investment

[5] In later sections we will extend this model by introducing revenue sharing, revelation strategies, and information acquisition investments. We introduce these model extensions at the begining of the respective sections that discuss these payoff structures and strategies.

with probability p (resp. $1-p$), with $0 < p < 1$.

Firms learn imperfectly about their cost of investment by the following signalling technology. When firms have high costs, nature always draws a bad signal, $t_i = \bar{t}$, for $i = 1, 2$. When costs of investment are low, firm i's signal depends on precision parameter R. Firm i receives a good signal, $t_i = \underline{t}$, with probability R, while the probability of a bad signal, $t_i = \bar{t}$, is $1 - R$, with $0 < R < 1$ and $i = 1, 2$. Signals are independently distributed between firms conditional on the firms' cost of investment. The first-stage stochastic structure for firm i is depicted in Figure 1 below. The dashed lines represent firm i's information sets.

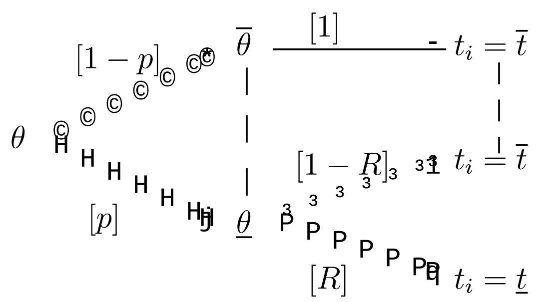

Figure 1: firm i's signal

We make different assumptions about the nature of the firms' signals. In particular we compare the outcome of a race where firms' signals are public information with the outcome of a race where signals are private information to firms. This comparison is made in section 4. Besides the fact that this comparison is interesting in itself, it also enables us to analyze a richer model in which firms strategically choose how much information to reveal to their rival. We introduce this extension to the model in section 6 of this paper. The precision of firms' signals will be endogenized in section 7 by assuming that firms make costly information acquisition investments.

Whenever a firm receives a good signal, $t_i = \underline{t}$, it learns that both firms have low costs of investment. Whenever both firms receive a bad public signal, they are in one of the following situations. Either they have high costs of investment, or firms have low costs and were simply unlucky. The extent to which firms were unlucky under a low cost project depends on precision parameter R. The higher the signal's precision, the more pessimistic firms become about their cost of investment after receiving bad public signals.

After firms received their signals, they invest in R&D by spending $D_i \in [0, 1]$. Firm i's probability of obtaining an innovation is D_i. In order to keep the model manageable, we assume that firm i's cost of investment is quadratic in R&D investment D_i, i.e. $c(D_i; \theta) = \frac{1}{2}\theta D_i^2$, for $i = 1, 2$.

At the end of the race there are three possible outcomes for the firms. The first outcome is one in which only one firm develops the innovation. The firm that develops the innovation, the winner, receives the winners' prize W, while the loser receives no revenue. The second outcome is one in which both firms successfully develop the innovation. In that case each firm receives prize T. Naturally, we assume that $0 \leq T \leq \frac{1}{2}W$. If both firms do not obtain the innovation, which is the third possible outcome, then neither firm receives revenues. Define $\Delta \equiv W - T$ as the difference between the prizes of winning and tying. Note that our assumption on T implies that $\frac{1}{2}W \leq \Delta \leq W$. Furthermore, we impose regularity condition $\underline{\theta} > 2\Delta$ to obtain interior solutions for firms' R&D investments. The firms' payoff structure is one in which the winner takes all. Although this is a common assumption in the R&D race literature, it is not necessarily realistic. In section 5 of the paper we analyze the effects of relaxing this assumption by introducing revenue sharing between the winner and loser of the race.

We assume that firms are risk-neutral. Given cost of investment θ and R&D investments $D \equiv (D_1, D_2)$, firm i's expected profits are:

$$\begin{aligned} \pi_i(D; \theta) &= D_i D_j T + D_i(1 - D_j)W - \frac{1}{2}\theta D_i^2 \\ &= D_i (W - \Delta D_j) - \frac{1}{2}\theta D_i^2. \end{aligned} \tag{1}$$

Then firm i's expected profit is as follows:

$$\Pi_i(R, D) = E_\theta\{\pi_i(D; \theta)|R\}. \tag{2}$$

We solve the game backwards, and focus on symmetric, pure-strategy Bayes-Nash equilibria.

3 Benchmark: Efficient R&D Investments

In this section we analyze the R&D investments that maximize expected total industry's profits. It is efficient for firms to receive public signals, since firms can always choose to ignore a public signal. We use the efficient outcome as a benchmark to study the effects of competition and private information on equilibrium strategies.[6]

After nature chose parameter θ and the firms' signals, $t_o \equiv (t_1, t_2)$, there are two basic states of the world. Either there is at least one firm that received a good signal, $\underline{t}_o \in \{(\underline{t}, \underline{t}), (\underline{t}, \overline{t}), (\overline{t}, \underline{t})\}$, or both firms received a bad signal, $\overline{t}_o \equiv (\overline{t}, \overline{t})$. In the first case both firms learn that they have a low cost of investment, and therefore expect $E(\theta|\underline{t}_o; R) = \underline{\theta}$. In the latter case firms cannot establish with certainty whether they will face a low or high cost of investment, and have expected cost of investment $E(\theta|\overline{t}_o; R) = \underline{\theta} + \phi(R)$, with:

$$\phi(R) \equiv \frac{(1-p)(\overline{\theta} - \underline{\theta})}{p(1-R)^2 + 1 - p}. \tag{3}$$

In the efficient outcome firm i chooses the investment that maximizes expected total profits, given the signals $t_o \in \{\underline{t}_o, \overline{t}_o\}$ and precision parameter R:

$$\max_{D_i \in [0,1]} E_\theta \left\{ \sum_{\ell=1} \pi_\ell(D;\theta) \Big| t_o; R \right\}, \text{ for } i = 1, 2. \tag{4}$$

The maximization gives the following first-order conditions for investments:

$$E(\theta|t_o; R) D_i = W - 2D_j\Delta, \text{ for } i, j = 1, 2, \text{ and } j \neq i. \tag{5}$$

Each firm's investment creates a negative externality on its rival's investment incentive. If firm i invests more in R&D, it becomes less likely that firm j will be the winner of the race, which depresses its expected prize. Firms' first-order conditions give the following efficient investments and *interim* expected profits for firm i, with $i = 1, 2$ and $t_o \in \{\underline{t}_o, \overline{t}_o\}$:

$$\overline{D}_i(t_o; R) = \frac{W}{E(\theta|t_o; R) + 2\Delta} \text{ and } \overline{\pi}_i(t_o; R) = \frac{1}{2}\overline{D}_i(t_o; R) W. \tag{6}$$

[6] Such a benchmark could be relevant for policy analysis when firms can fully appropriate the social value of their innovation.

Note that it is efficient to invest less after observing $(\bar{t}, \bar{t})$ than after observing a good signal, i.e. $\overline{D}_i(\underline{t}_o; R) > \overline{D}_i(\bar{t}_o; R)$ for $i = 1, 2$. Two bad signals make firms increasingly pessimistic about their costs of investment when the signals' precision grows, and therefore $\partial \overline{D}_i(\bar{t}_o; R)/\partial R < 0$, for $i = 1, 2$.

For future use we define firm i's expected *ex ante* efficient investments and profits respectively as:

$$\begin{aligned} \overline{D}_i(R) &\equiv p[1-(1-R)^2]\overline{D}_i(\underline{t}_o; R) + [p(1-R)^2 + 1 - p]\overline{D}_i(\bar{t}_o; R), \quad (7) \\ \overline{\Pi}_i(R) &\equiv \frac{1}{2}\overline{D}_i(R)W. \quad (8) \end{aligned}$$

Finally we show how expected efficient investments and profits depend on the signals' precision R. An increase in the signals' precision has two opposing effects on expected efficient investments, as summarized in the following expression:

$$\overline{D}_i'(R) = 2p(1-R)\left(\overline{D}_i(\underline{t}_o; R) - \overline{D}_i(\bar{t}_o; R)\right) + [p(1-R)^2 + 1 - p]\frac{\partial \overline{D}_i(\bar{t}_o; R)}{\partial R}. \quad (9)$$

In case firms invest in a low-cost project, an increase in the signals' precision increases the firms' probability of receiving a good signal. This direct effect increases the firms' expected investments. On the other hand, in case firms receive bad signals, an increase of precision makes them more pessimistic about their cost of investment. This indirect effect lowers the firms' expected investments. It is easy to show that the direct effect outweighs the indirect effect. Therefore the expected efficient investments and profits are monotonically increasing in the precision of the public signals, i.e. $\overline{D}_i'(R) > 0$ and $\overline{\Pi}_i'(R) > 0$. We summarize our results in the following lemma.

Lemma 1 *The efficient R&D investments are such that, for all* R *and* $i = 1, 2$*: (i) Investments after a good signal exceed those after two bad signals:* $\overline{D}_i(\underline{t}_o; R) > \overline{D}_i(\bar{t}_o; R)$*; (ii) Investments after two bad signals decrease, while ex ante expected investments increase in the signals' precision:* $\partial \overline{D}_i(\bar{t}_o; R)/\partial R < 0$*, while* $\overline{D}_i'(R) > 0$*; (iii) Ex ante expected efficient profits increase monotonically in the signals' precision:* $\overline{\Pi}_i'(R) > 0$*.*

4 Winner-Take-All Race

In this section we analyze investment incentives and profits of competing firms. We compare the equilibrium of the race with public signals, with the equilibrium of the race with private signals.

4.1 Public Signals

In this subsection we analyze the equilibrium of the R&D race where signals t_o are publicly observable. We derive equilibrium investments and profits of noncooperative firms, and analyze how they relate to the efficient outcome.

The qualitative properties of equilibrium R&D investments and profits are identical to those of the efficient outcome. After observing the signals, t_o, and given precision R, firm i chooses the investment that maximize its expected profit. This gives the following first-order conditions:

$$E(\theta|t_o;R)D_i = W - D_j\Delta, \text{ for } i,j = 1,2, \text{ and } j \neq i, \tag{10}$$

with $E(\theta|\underline{t}_o;R) = \underline{\theta}$, and $E(\theta|\overline{t}_o;R) = \underline{\theta} + \phi(R)$.

The following equilibrium investments and *interim* expected profits result from both firms' first-order conditions:

$$\widehat{D}_i(t_o;R) = \frac{W}{E(\theta|t_o;R) + \Delta} \text{ and } \widehat{\pi}_i(t_o;R) = \frac{1}{2}E(\theta|t_o;R)\widehat{D}_i(t_o;R)^2, \tag{11}$$

for all t_o, R and $i = 1,2$. The qualitative properties for efficient investments, as summarized in lemma 1 (i)-(ii), also hold for these equilibrium investments.

The quantitative comparison between efficient and equilibrium investments gives overinvestment: $\widehat{D}_i(t_o;R) > \overline{D}_i(t_o;R)$ for all t_o, R and $i = 1,2$. Competing firms invest more in R&D, because they do not internalize the negative effect of their own R&D investments on their rival's expected revenues. Firm i's investment D_i marginally decreases firm j's revenue with $D_j\Delta$. Therefore firms invest more aggressively than is efficient. This is a common observation in the literature on R&D races.

Firm i's *ex ante* expected equilibrium investment and profit are as follows:

$$\begin{aligned}
\widehat{D}_i(R) &\equiv p[1-(1-R)^2]\widehat{D}_i(\underline{t}_o;R) + [p(1-R)^2 + 1 - p]\widehat{D}_i(\overline{t}_o;R), \quad (12)\\
\widehat{\Pi}_i(R) &\equiv p[1-(1-R)^2]\widehat{\pi}_i(\underline{t}_o;R) + [p(1-R)^2 + 1 - p]\widehat{\pi}_i(\overline{t}_o;R). \quad (13)
\end{aligned}$$

When we compare this profit with the firm's *ex ante* expected efficient profit, we observe the following. First, the negative externality makes expected equilibrium profits strictly lower than the efficient expected profits. Second, competing firms trade off qualitatively similar effects after the signal's precision increases as total-profit maximizing firms do. The effects on expected profits are summarized in the following expression:

$$\begin{aligned}\hat{\Pi}_i'(R) &= p(1-R)\underline{\theta}\left(\hat{D}_i(\underline{t}_o;R)^2 - \hat{D}_i(\bar{t}_o;R)^2\right) + \\ &\quad +[p(1-R)^2+1-p](\underline{\theta}+\phi(R))\hat{D}_i(\bar{t}_o;R)\frac{\partial \hat{D}_i(\bar{t}_o;R)}{\partial R}. \qquad (14)\end{aligned}$$

Again the positive direct effect dominates the negative indirect effect, i.e. $\hat{\Pi}_i'(R) > 0$ for all R.

We summarize the subsection's findings in the following lemma.

Lemma 2 (Public Signals) *Firm i with public signals overinvests in equilibrium: $\hat{D}_i(t_o;R) > \overline{D}_i(t_o;R)$ for all t_o and R, with $i=1,2$. Ex ante equilibrium profits are strictly lower than efficient expected profits: $\hat{\Pi}_i(R) < \overline{\Pi}_i(R)$ for all R. Moreover all qualitative properties of lemma 1 hold true for $\hat{D}_i(t_o;R)$, $\hat{D}_i(R)$, and $\hat{\Pi}_i(R)$ as well.*

4.2 Private Signals

In this subsection we derive the equilibrium investments and profits under the assumption that signals are private information to the firms and cannot be revealed to rivals. We compare this equilibrium with the equilibrium under public signals.

With private signals, the following reaction functions determine the firms' equilibrium R&D investments (with $i,j=1,2$, $i \neq j$):

$$\underline{\theta}\tilde{D}_i(\underline{t};R) = W - \left(R\tilde{D}_j(\underline{t};R) + (1-R)\tilde{D}_j(\bar{t};R)\right)\Delta, \qquad (15)$$

$$(\underline{\theta}+\varphi(R))\,\tilde{D}_i(\bar{t};R) = W - \left(P(R)\tilde{D}_j(\underline{t};R) + [1-P(R)]\tilde{D}_j(\bar{t};R)\right)\Delta \qquad (16)$$

with

$$\varphi(R) = \frac{(1-p)(\overline{\theta}-\underline{\theta})}{1-pR} \text{ and } P(R) = \frac{p(1-R)R}{1-pR}. \qquad (17)$$

We first establish that the qualitative properties of lemma 1 (i)-(ii) also hold for equilibrium investments under private signals. A firm with a good private signal is more optimistic about its expected costs of investment, but expects fiercer competition than a firm with a bad signal. Since the cost effect outweighs the competition effect, firms with a bad private signal invest less than firms with a good private signal.

The equilibrium investments depend on the signal's precision R in the following way. A firm with a good signal expects a more optimistic rival after the signals' precision increases, which depresses the firm's investments. A firm that receives a bad signal, trades off the following conflicting effects. On the one hand, an increase in the signals' precision makes the firm more pessimistic about the costs of investment, i.e. $\varphi(R)$ increases, which lowers its investments. On the other hand, the firm expects weaker competition, i.e. $P(R)$ decreases, which encourages its investments. Again the negative cost effect outweighs the positive competition effect. Therefore firms' equilibrium investments decrease in the signals' precision.

For the comparison of equilibrium R&D investments of firms with private and public signals we observe the following. Privately informed firms can condition their R&D investments only on their own signal. A good signal received by one firm does not imply that both firms become optimistic about the cost of investment. It is possible that the other firm is unlucky and receives a bad signal. Therefore the expected rival to a firm with a good private signal is less aggressive than the rival to a firm with a good public signal. This makes equilibrium investments of a firm with a good private signal exceed those of a firm with a good public signal: $\tilde{D}_i(\underline{t}; R) \geq \hat{D}_i(\underline{t}_o; R)$ for all R.

Now consider the situation in which nature chose two bad signals, $t_o = (\bar{t}, \bar{t})$. For each firm there are two conflicting effects when we turn from a public to a private bad signal. On the one hand a firm with only one bad signal is more optimistic about costs of investment, because it does not pool information with his rival. On the other hand, the privately informed firm expects a more aggressive rival since the rival could be optimistic. The first effect encourages, while the second effect discourages investments. The direct cost effect outweighs the indirect competition effect. Therefore a firm with a private bad signal invests more in R&D than a firm with public bad signals: $\tilde{x}_i(\bar{t}; R) > \hat{x}_i(\bar{t}_o; R)$ for all R.

From these observations we cannot conclude that overall firms with private signals invest more in R&D than firms with public signals. In the race with public signals the firms' likelihood of receiving a good signal is bigger than in the race with private signals. Although firms' equilibrium investments are higher given a private signal, the higher likelihood of receiving a good public signal makes expected equilibrium investments with public signals higher: $\tilde{x}_i(R) < \hat{x}_i(R)$, for all R, where

$$\tilde{x}_i(R) \equiv pR\tilde{x}_i(\underline{t}; R) + (1 - pR)\tilde{x}_i(\bar{t}; R). \tag{18}$$

That is, overall the expected equilibrium investments for firms with public signals are higher than those with privately observable signals.

We summarize our findings on equilibrium investments in the following proposition.

Proposition 1 (Investments) *In the race with private signals equilibrium R&D investments are such that, for $i = 1, 2$:*
Given received signals, firms invest more after receiving a private signal than after receiving public signals: $\tilde{x}_i(\underline{t}; R) > \hat{x}_i(\underline{t}_o; R)$ and $\tilde{x}_i(\bar{t}; R) > \hat{x}_i(\bar{t}_o; R)$, for all R. However, for the ex ante expected equilibrium investments the reverse holds: $\tilde{x}_i(R) < \hat{x}_i(R)$. Moreover, the qualitative properties of lemma 1 (i)-(ii) also hold for $\tilde{x}_i(t_i; R)$ and $\tilde{x}_i(R)$.

In the remainder of this section we analyze how expected equilibrium profits compare. First we compare the firms' *interim* expected profits. The *interim* expected profits of a firm with private signals are as follows:

$$\tilde{\pi}_i(t_i; R) = \frac{1}{2}E(\theta|t_i; R)\tilde{x}_i(t_i; R)^2, \tag{19}$$

where $E(\theta|\underline{t}; R) = \underline{\theta}$ and $E(\theta|\bar{t}; R) = \underline{\theta} + \varphi(R)$. A firm that received a good signal invests less in the equilibrium of the race with public signals than in the race with private signals, and expects the same cost parameter $E(\theta|\underline{t}; R) = \underline{\theta}$ in both races. Therefore a firm with a good public signal expects lower profits than a firm with a good private signal: $\widehat{\pi}_i(\underline{t}_o; R) < \widetilde{\pi}_i(\underline{t}; R)$. If both firms receive bad signals, there are two conflicting factors in their expected profit functions. On the one hand each firm invests less in the equilibrium of the race with public signals than in the race with private signals. On the other hand each firm is more pessimistic about cost parameter θ in the race with public signals, i.e. $\phi(R) > \varphi(R)$. Therefore the profit comparison for pessimistic firms is not obvious. We obtain that if $\underline{\theta} \geq 3\Delta$, the expected equilibrium profits in the race with public bad signals are lower than those in the race with private bad signals: $\widehat{\pi}_i(\overline{t}_o; R) < \widetilde{\pi}_i(\overline{t}; R)$.

Second, we compare the firms' *ex ante* expected profits under public and private signals. Firm i's *ex ante* expected equilibrium profit of receiving private signals is as follows:

$$\widetilde{\Pi}_i(R) \equiv pR\widetilde{\pi}_i(\underline{t}; R) + (1 - pR)\widetilde{\pi}_i(\overline{t}; R). \tag{20}$$

If $\underline{\theta} \geq 3\Delta$, then firms expect higher profits from a more informative signal, i.e. $\widetilde{\Pi}_i'(R) > 0$. When we compare this $\widetilde{\Pi}_i(R)$ with $\widehat{\Pi}_i(R)$ we observe two conflicting effects. For given signals and $\underline{\theta} \geq 3\Delta$, firms expect higher *interim* equilibrium profits in the race with private signals. This favors *ex ante* expected equilibrium profits in the race with private signals. However the probability of receiving a good public signal, and consequently expecting high equilibrium profits, is greater in the race with public signals. This effect benefits firms's expected equilibrium profits in the race with public signals. The trade-off between the two effects is summarized in part (ii) of the following proposition.

Proposition 2 (Profits) *(i) If $\underline{\theta} \geq 3\Delta$, firms that receive a private signal expect higher profits than firms that receive public signals: $\widetilde{\pi}_i(\underline{t}; R) > \widehat{\pi}_i(\underline{t}_o; R)$, and $\widetilde{\pi}_i(\overline{t}; R) > \widehat{\pi}_i(\overline{t}_o; R)$ for all R and $i = 1, 2$. (ii.a) If $3\Delta < \underline{\theta} < (2 + \sqrt{3})\Delta$ and $\overline{\theta}$ sufficiently small, there are critical precisions R' and R'' with $0 < R' \leq R'' < 1$ such that $\widehat{\Pi}_i(R) < \widetilde{\Pi}_i(R)$ for all $R \leq R'$, while $\widehat{\Pi}_i(R) > \widetilde{\Pi}_i(R)$ for all $R \geq R''$. (ii.b) If $\underline{\theta} \geq (2 + \sqrt{3})\Delta$, firms expect higher profits in the race with public signals than in the race with private signals, i.e. $\widehat{\Pi}_i(R) > \widetilde{\Pi}_i(R)$ for all R. Moreover, if $\underline{\theta} \geq 3\Delta$, the qualitative property of lemma 1 (iii) also holds for $\widetilde{\Pi}_i(R)$.*

The expected profit comparisons would indicate the firms' incentives to share information, if each firm could commit to share before it receives its signal. In section 6 we study whether firms actually share information after they received their signals.

5 Revenue Sharing

So far we assumed that in the race the winner takes all. This is, however, only an extreme way of distributing revenues from the innovation among firms. In this section we assume that the loser of the race gets a share of the revenues from the winner. In an R&D race revenue sharing can be implemented by license agreements between competitors, see e.g. Shapiro (1985). We show that revenue sharing introduces free-rider incentives in the R&D investment stage, which reduces overinvestments. The effects of revenue sharing on R&D feed back in the firms' incentives for information revelation and acquisition incentives, as we show in subsequent sections.

We assume that the loser of the race receives share σ of the revenues from the winner. Hence the winner of the race receives prize $(1-\sigma)W$, while the loser receives the remainder of the prize, i.e. σW, with $0 \leq \sigma \leq 1$. Observe that for $\sigma = 0$, we are in the "winner-take-all" race, while for $\sigma = \frac{1}{2}$ firms share the prize equally.

Given revenue share σ and cost parameter θ R&D profits are:

$$\begin{aligned} \pi_i(D;\theta|\sigma) &= D_i D_j T + D_i(1-D_j)(1-\sigma)W + (1-D_i)D_j\sigma W - \frac{1}{2}\theta D_i^2 \\ &= D_i((1-\sigma)W - \Delta D_j) - \frac{1}{2}\theta D_i^2 + D_j\sigma W. \end{aligned} \tag{21}$$

This changes first-order conditions for R&D investments into:

$$E(\theta|t_\ell, R)D_i = (1-\sigma)W - E_{t\cdot}(D_j|t_\ell, R)\Delta, \tag{22}$$

with $E(\theta|t_\ell, R)$ and $E_{t\cdot}(D_j|t_\ell, R)$ the expected costs and expected rival's investment, respectively, for $\ell \in \{o, i\}$, $i, j, = 1, 2$ and $i \neq j$. Note that marginal expected revenues are reduced by σW due to revenue sharing, while marginal costs remain the same. Therefore, equilibrium R&D investments decrease in the revenue share σ. The marginal effect of firm i's R&D investment on firm

j's expected profits is now $\sigma W - D_j\Delta$. Hence the negative externality $-D_j\Delta$ of the winner-take-all race is reduced by σW. Sharing revenues makes firms less aggressive competitors, because their profits are more interdependent.

In equilibrium the R&D investments and profits relate as follows to the winner-take-all equilibrium investments and profits:[7]

$$D_i(.|\sigma) = (1-\sigma)D_i(.), \text{ and} \tag{23}$$

$$\pi_i(.|\sigma) = (1-\sigma)[(1-\sigma)\pi_i(.) + \sigma W E_t(D_j|.)]. \tag{24}$$

for $i = 1, 2$. Equilibrium investments are monotonously decreasing in the revenue share. Initially revenue sharing decreases overinvestments, which increases equilibrium profits. A further increase in the revenue share results in equilibrium underinvestments, which decreases profits. Therefore, equilibrium profits are initially increasing, and subsequently decreasing in the revenue share. These results are summarized in the following proposition.

Proposition 3 (Interim) *The following holds both for races with public and for races with private signals, for all t and R. (i) Equilibrium investments decrease in the revenue share: $\partial D_i(.|\sigma)/\partial\sigma < 0$ for all $\sigma < 1$. (ii) Equilibrium profits initially increase in σ, and subsequently drop to zero: there is a share $\sigma' \in (0, \frac{1}{2})$ s.t. $\partial\pi_i(.|\sigma)/\partial\sigma > 0$ for all $\sigma < \sigma'$ and $\partial\pi_i(.|\sigma)/\partial\sigma < 0$ for all $\sigma > \sigma'$ for all t and R.*

When firms share revenues, firm i's *ex ante* expected equilibrium profit is as follows:

$$\Pi_i(R|\sigma) = (1-\sigma)\left[(1-\sigma)\Pi_i(R) + \sigma W D_j(R)\right], \tag{25}$$

The expected revenue spillover from each firm's rival increases in the signals' precision, i.e. $D_j'(R) > 0$, as we saw in the previous section. Therefore, if $\underline{\theta} \geq 3\Delta$, the expected equilibrium profits are monotonically increasing in the precision of the signals, i.e. $\partial\Pi_i(R|\sigma)/\partial R > 0$ for all R.

Although the firms' revenue share is exogenously determined, it is instructive to check whether the efficient profit level can be obtained by revenue

[7] Since for most of this section the characterizations of equilibrium profits and investments are qualitatively identical for the races with public and private signals, we drop the decorations and arguments of equilibrium investment and profit functions.

sharing. For each precision of the signals R, we can calculate the maximally attainable expected equilibrium profits from revenue sharing. We do this by inserting the profit maximizing revenue share $\sigma(R)$ in the profit function. It is easily verified, and shown in proposition 3, that $2\Pi_i(R) < D_j(R)$, and therefore the profit maximizing revenue share equals:

$$\sigma(R) = \frac{D_j(R)W - 2\Pi_i(R)}{2\left[D_j(R)W - \Pi_i(R)\right]}. \tag{26}$$

The profit maximizing revenue share creates a race that is strictly between winner-take-all and equal-sharing, i.e. $0 < \sigma(R) < \frac{1}{2}$. After we substitute $\sigma(R)$ in the expected profit function, we obtain the maximally attainable equilibrium profits:

$$\Pi_i\left(R|\sigma(R)\right) = \frac{D_j(R)^2W^2}{4\left[D_j(R)W - \Pi_i(R)\right]}. \tag{27}$$

If $\underline{\theta} \geq 3\Delta$, these maximum expected profits compare as follows for all R:

$$\widetilde{\Pi}_i(R|\widetilde{\sigma}(R)) < \widehat{\Pi}_i(R|\widehat{\sigma}(R)) < \overline{\Pi}_i(R), \tag{28}$$

The fact that $\widetilde{\Pi}_i(R|\widetilde{\sigma}(R)) < \widehat{\Pi}_i(R|\widehat{\sigma}(R))$ does, however, not imply that for a given revenue share σ publicly informed firms expect higher equilibrium profits than privately informed firms. An illustration of this fact was presented in the previous section for the winner-take-all race, see e.g. proposition 2 (ii.a). For all R the maximally attainable equilibrium profits are strictly below the efficient expected profits, as we show in the following proposition. Revenue sharing can therefore never implement the efficient outcome.

Proposition 4 (Ex ante) *(i) Irrespective of whether signals are public and private information, expected profits are maximized in a race that is strictly between winner-take-all and equal-sharing:* $0 < \sigma(R) < \frac{1}{2}$ *for all R. (ii.a) Firms' expected equilibrium profits are always strictly lower than the expected efficient profits:* $\max\left\{\widehat{\Pi}_i(R|\sigma), \widetilde{\Pi}_i(R|\sigma)\right\} < \overline{\Pi}_i(R)$ *for all* σ *and R. (ii.b) In particular, if* $\underline{\theta} \geq 3\Delta$*, then the maximal expected profits for a firm with public signals exceeds the maximal expected profits of a firm with private signals:* $\widetilde{\Pi}_i(R|\widetilde{\sigma}(R)) < \widehat{\Pi}_i(R|\widehat{\sigma}(R))$*, for all R. (iii) Moreover, if* $\underline{\theta} \geq 3\Delta$*, then for any revenue share the qualitative property of lemma 1 (iii) also holds for ex ante expected equilibrium profits.*

6 Strategic Revelation

In this section we extend the basic model by adding an information revelation stage. After firms received their private signal, each firm chooses what information to reveal. Subsequently firms invest in R&D. Firms have an incentive to manipulate their information in order to alter their rival's beliefs, and consequently change R&D competition in their favor.

We make two distinct informational assumptions. We analyze what information firms reveal when signals are non-verifiable in the next subsection. The second subsection studies how firms' incentives and possibilities to reveal information are affected when information is costlessly verifiable.

6.1 Non-verifiable Information

In this subsection we assume that firms cannot verify the truthfulness of their rival's messages. Since information is non-verifiable, firms can make any statement about their signal they like. Formally, after each firm received its private signal, firms simultaneously choose their revelation rules $(\tau_i(\underline{t}), \tau_i(\overline{t}))$, with $\tau_i(t_i) \in \{\underline{t}, \overline{t}\}$, and reveal information $\hat{t}_i \in \{\tau_i(t_i) | t_i = \underline{t}, \overline{t}\}$ accordingly. We assume that firms' revelation rules do not depend on the signal's precision R. For example, revelation rule $(\tau_i(\underline{t}), \tau_i(\overline{t})) \equiv (\underline{t}, \overline{t})$ gives truthful revelation, while rules $(\tau_i(\underline{t}), \tau_i(\overline{t})) \equiv (\overline{t}, \overline{t})$ and $(\underline{t}, \underline{t})$ do not reveal any information to the rival firm. After messages are sent, firms simultaneously invest in R&D.

A natural first step of analysis is to see whether firms voluntarily reveal all their information in equilibrium. This would give us R&D investments of the race with public signals. First consider the winner-take-all race. In this race each firm has an incentive to make its rival invest as little as possible. If it is expected that a firm fully reveals its information, then this firm has an incentive to always send bad news, i.e. it always states $\hat{t}_i = \overline{t}$. The rival believes this is truthfully revealed information, and becomes pessimistic. The pessimistic rival invests little in R&D, which increases the expected profit of the sender of bad news. Second, consider the equal-sharing race where firms believe that their rival fully reveals information. In an equal-sharing race each firm has an incentive to make his rival's investments as big as possible in order to take a free ride on those investments. Then a firm has an incentive to always send good news. The firm's rival believes that $\underline{t}$ was observed, and becomes optimistic about the costs of investment. The rival's investments increase, and the sender of good news takes a free ride on these high investments. Similar incentives to under- or overstate signals exist for other revenue shares. And full disclosure does never happen in equilibrium, as is stated in the following proposition.

Proposition 5 (No Full Revelation) *For all revenue shares $\sigma \in [0, 1]$, there does not exist an equilibrium of the game with strategic revelation of non-verifiable information in which signals are fully revealed.*

The polar case of complete revelation is no revelation of any information. No revelation of information can always be sustained as an equilibrium. Given that the statements of firms contain no information whatsoever, firms ignore them. Since statements are ignored, neither truthful nor false statements affect rival's investments. Therefore firms are indifferent between all statements, and it is optimal to choose the non-revealing rule that is consistent with equilibrium beliefs. This is stated in the following lemma.

Lemma 3 (No Revelation) *There is an equilibrium of the game with strategic revelation of non-verifiable information in which no information is revealed for any revenue share $\sigma \in [0, 1]$.*

This result is similar to that of Ziv (1993), and is standard for models with non-verifiable signals. The paper by Ziv focuses on the incentives of Cournot duopolists to understate costs of producing homogeneous products. In our analysis we consider a situation in which revenue sharing affects firms' incentives. And we show that irrespective of how firms share the revenue from innovation, they never reveal their information.

Our contribution is here to show that even for intermediate revenue shares firms' incentives are not aligned. Depending on how much of the revenue is shared between firms, firms have an incentive to give less (low σ), more (high σ), or both less and more (intermediate σ) favorable information to the rivals. Although *ex ante* expected profits are often higher for firms that invest with public signals, firms cannot reach this equilibrium by strategically revealing non-verifiable signals.

An interesting extension to this section's analysis would be to study whether there are revenue shares for which firms reveal some information in equilibrium. Such an analysis awaits future research.

6.2 Verifiable Information

In the previous subsection we assumed that firms can costlessly misrepresent their private signals. Therefore credible revelation of information is not possible in equilibrium. A natural question to ask is how the results change when information is costlessly verifiable. The only choice that a firm with verifiable information has, is to either disclose its information or conceal it. That is, firms simultaneously choose revelation rules $(\tau_i(\underline{t}), \tau_i(\overline{t}))$, with $\tau_i(t_i) \in \{t_i, \varnothing\}$ for $t_i \in \{\underline{t}, \overline{t}\}$ and $i = 1, 2$.

The seminal paper by Okuno-Fujiwara *et al.* (1990) gives sufficient conditions on firms' strategic interaction and information under which an equilibrium with full disclosure of private information with sceptical inferences exists. For our R&D race neither sufficient condition 4c nor 4d from Okuno-Fujiwara *et al.* (1990) are met. Assumption 4c (resp. 4d) states that as a firm's signal increases, his reaction curve shifts out (resp. in) while his rival's reaction function shifts in (resp. out) or stays the same.

In our model firms' signals, and expected profits, are correlated. Therefore firm i's marginal expected profit is non-increasing both in its own and its rival's signal. The negative relationship between a firm's disclosure and its own marginal profit is a strategic effect. After disclosing verifiable good news, a firm discloses to be an aggressive investor, which shifts out its reaction function. The negative relationship between a firm's signal and its rival's marginal profit is caused by the informational effect of disclosure. Disclosure of good news by one firm makes the firm's rival more optimistic which shifts out his reaction function.

The violation of the sufficient conditions for complete revelation raises the question whether the "unraveling" result still holds. Okuno-Fujiwara *et al.* discuss a common value example in which neither condition 4c nor

4d is satisfied, but full disclosure is still established. The result is obtained here because the strategic effect dominates the informational effect. In our model the informational effect dominates the strategic effect, and we obtain a similar result for extreme revenue shares. However for intermediate revenue shares unraveling does not occur.

Proposition 6 (Verifiable Information) *If firms' signals are costlessly verifiable after revelation, then there are revenue shares* $\underline{\sigma}$ *and* $\overline{\sigma}$ *, with* $0 < \underline{\sigma} < \overline{\sigma} < 1$*, such that:*
(i) for $\sigma \leq \underline{\sigma}$ *firms fully disclose in equilibrium with skeptical inferences,*
(ii) for $\underline{\sigma} < \sigma < \overline{\sigma}$ *no inferences support full disclosure in equilibrium,*
(iii) for $\sigma > \overline{\sigma}$ *firms fully disclose in equilibrium with skeptical inferences.*

For low (resp. high) revenue shares firms have an incentive to disclose only bad (resp. good) news. A firm's rival anticipates this and knows that a concealing firm's cost signal is low (resp. high). This evaporates a firm's possibilities to effectively conceal information. The verifiability of firms' information enables a firm to unravel its rival's private information, as in Grossman (1981) and Milgrom (1982). This result is the opposite of our results on revelation in the previous subsection. For non-verifiable signals firms cannot credibly reveal any information, while for verifiable signals firms cannot credibly conceal information from their rival.

In races with intermediate revenue shares complete disclosure is not an equilibrium strategy. Since both the optimistic and pessimistic investors have an incentive to misrepresent their signals, full disclosure is not chosen in equilibrium. A firm that received a bad signal has an incentive to conceal since it makes its rival more optimistic about the costs of investment. The rival will invest more in R&D, and the concealing firm can take a free ride on these higher investments. A firm with a good signal has an incentive to conceal information, and discourage its rival in the investment stage. For the good-signal firm the informational effect outweighs the free-rider effect. A similar result is found in a different setting by Hendricks and Kovenock (1989).

The results of this section indicate that the assumption of publicly observable signals, as in Choi (1991) and Malueg and Tsutsui (1997), need not always be sustainable as firms' equilibrium strategies. When the assumption is relaxed and signals can be costlessly misrepresented, complete revelation no longer happens in equilibrium. With verifiable signals public signals are a proper assumption if revenue shares are extremely low or high. The amount of information that can and will be shared among firms crucially depends on the verifiability of this information, and on the appropriability of the innovation's revenues.

7 Strategic Information Acquisition

In sections 3-6 we showed that generically firms would increase their expected profits if they could increase the precision of their signals. This section discusses individual firms' incentives to invest in acquiring a more informative signal, i.e. we endogenize the signal's precision. Whether signals are public or private does not only affect firms' incentives to invest in R&D, but also affects incentives to acquire those signals. This section studies how the information acquisition investments interact with the R&D investments.

Instead of assuming that the firms' signals are of exogenous precision, we assume that each firm invests $R_i \in [0, 1]$ in receiving a signal from nature. If the firms have low costs of investment, and firm i invests R_i in information acquisition, it receives signal $t_i = \underline{t}$ with probability R_i. Firm i's cost of information acquisition is $c(R_i) = \frac{1}{2}\rho R_i^2$. For convenience, and relevance, we assume that these investments are unobservable. Firm i expects information acquisition investment r_j from firm j. The sequence of moves is as follows. After nature chooses the cost of R&D investment, firms simultaneously invest in information acquisition. After the firms received their signals they invest in R&D. We compare firms' information acquisition incentives for the race with public signals with those for the race with private signals.

7.1 Efficient Information Acquisition

Efficient information acquisition investments maximize the sum of *ex ante* expected efficient profits. Firm i's first-order condition of this maximization problem, after the subsequent imposition of symmetry on investments ($R_i = R$), is as follows:[8]

$$\rho R = p(1-R)\left(\sum_{\ell=1} \pi_\ell \left(\overline{D}(\underline{t}_o;R);\underline{\theta}\right) - \sum_{\ell=1} \pi_\ell \left(\overline{D}(\bar{t}_o;R);\underline{\theta}\right)\right). \tag{29}$$

This first-order condition determines firm i's efficient information acquisition investment $\overline{R}_i$. That is, marginal costs equal marginal revenues of information acquisition investments. Marginal costs are the direct cost of information acquisition investment, ρR. The marginal revenue of information acquisition is the total profit gained from obtaining a good signal and finding out that costs of investment are low after investing a marginal amount more.

7.2 Public Signal Information Acquisition

In the race with public signals each firm chooses the information acquisition investment that maximizes its expected profit, given equilibrium R&D investments. Firm i's first-order condition for profit-maximization, with symmetric investments (i.e. $R_i = R$) and realized expectations (i.e. $r_i = R$), is as follows:

$$\rho R = \max\left\{0, (1-\sigma)\left((1-\sigma)\widehat{MR}(R) + \sigma \widehat{MQ}(R)\right)\right\}, \tag{30}$$

with

$$\widehat{MR}(R) \equiv p(1-R)\left[\pi_i\left(\hat{D}(\underline{t}_o;R);\underline{\theta}\right) - \pi_i\left(\hat{D}(\bar{t}_o;R);\underline{\theta}\right)\right], \text{ and} \tag{31}$$

$$\widehat{MQ}(R) \equiv p(1-R)W\left[\hat{D}_j(\underline{t}_o;R) - \hat{D}_j(\bar{t}_o;R)\right]. \tag{32}$$

The two terms of firm i's marginal revenues represent the following two effects of information acquisition. The first term captures the marginal increase in revenue after more information acquisition results in discovering a low cost of investment. This term is similar to the marginal revenue of efficient information acquisition. The second term represents the change in revenue that firm i expects to receive from its rival after making him more optimistic

[8] See the Appendix for the derivation of this condition.

by acquiring a good signal for the industry. Firm i's second-order condition for equilibrium information acquisition investments is expression (48) in the Appendix. The investment $\hat{h}_i(\sigma)$ that satisfies both the first- and second-order conditions is firm i's equilibrium information acquisition investment.

In the winner-take-all race ($\sigma = 0$) firms underinvest in information acquisition. If firm i acquires a good signal, this improves both its own and its rival's expected profit, since the signal is public and firms learn from each other's signal. This gives firms an incentive to free-ride on their rival's information acquisition investment, and underinvest in equilibrium as is stated in proposition 7 (i).

When we increase the firms' revenue share ($\sigma > 0$), this has the following conflicting effects on the firms' information acquisition incentives. On the one hand the revenue share internalizes a fraction of the positive externality from information acquisition. The internalization of the free-rider effect in acquiring public signals increases firms' information acquisition incentives. However, an increase in the revenue share diminishes the firms' incentives to invest in R&D, and consequently their marginal information acquisition revenues. The creation of a free-rider effect in R&D decreases the firms' incentives to acquire information. The equilibrium information acquisition investment depends on the trade-off between these two conflicting effects. Initially the positive effect of revenue sharing dominates, while for a sufficiently big revenue share the negative effect dominates. Therefore the equilibrium information acquisition investment initially increases and subsequently decreases as firms share more of their revenues. Whether there is a revenue share such that the equilibrium information acquisition investment rises above the efficient investment depends on parameter values. This is summarized in proposition 7 (ii).

Revenue sharing affects the firms' incentives to acquire information, as well as incentives to invest in R&D. This raises the question what the overall effect of revenue sharing on the firms' *ex ante* expected equilibrium profits is. Firm i's expected equilibrium profit given equilibrium information acquisition and R&D investments is defined as follows:

$$\hat{\Pi}_i(\sigma) \equiv \Pi_i\left(\hat{h}(\sigma)\,\middle|\,\sigma\right). \tag{33}$$

The effect of revenue sharing on expected profit can be decomposed as follows:

$$\widehat{\Pi}_i'(\sigma) = \frac{\partial \widehat{\Pi}_i\left(\widehat{R}(\sigma)\middle|\sigma\right)}{\partial R}\cdot \widehat{R}'(\sigma) + \frac{\partial \widehat{\Pi}_i\left(\widehat{R}(\sigma)\middle|\sigma\right)}{\partial \sigma} \tag{34}$$

Proposition 4 already shows that expected profits are increasing in the signal's precision, i.e. $\partial \widehat{\Pi}_i(R|\sigma)/\partial R > 0$. Moreover in the previous paragraph we established that the equilibrium information acquisition investment initially increases and subsequently decreases in the revenue share. This implies that the first term of expression (34) is positive for low revenue shares, and negative for high revenue shares. For the second term of expression (34) we observed in proposition 3 that profits are initially increasing in the revenue share and subsequently decreasing. When we add the two terms we conclude that for sufficiently low revenue shares expected *ex ante* profits increase after an increase in the revenue share, while for sufficiently high revenue shares expected profits decrease in the revenue share. Therefore there is an intermediate revenue share that maximizes expected *ex ante* profits. This is stated in part (iii) of the following proposition.

Proposition 7 *Suppose that the second-order condition for information acquisition is satisfied. (i) Equilibrium information acquisition investments in the winner-take-all race with public signals do not exceed the efficient investments:* $\overline{R}_i \geq \widehat{R}_i(0)$ *for* $i = 1, 2$. *(ii) There are revenue shares* $\widehat{\sigma}_0^I, \widehat{\sigma}_1^I$, *with* $0 < \widehat{\sigma}_0^I \leq \widehat{\sigma}_1^I < 1$, *such that equilibrium information acquisition investments are non-decreasing for all* $\sigma < \widehat{\sigma}_0^I$ *and decreasing for all* $\sigma > \widehat{\sigma}_1^I$. *In particular, if* $E(\theta) > \sqrt{2(\underline{\theta}^2 + 2\underline{\theta}\Delta + 2\Delta^2)}$, *then* $\overline{R}_i \geq \widehat{R}_i(\sigma)$ *for all* σ *and* $i = 1, 2$. *(iii) There are critical values* $\widehat{\sigma}_0^{II}$ *and* $\widehat{\sigma}_1^{II}$ *with* $0 < \widehat{\sigma}_0^{II} \leq \widehat{\sigma}_1^{II} < 1$ *such that* $\widehat{\Pi}_i(\sigma)$ *increases in* σ *for all* $\sigma \leq \widehat{\sigma}_0^{II}$, *and decreases in* σ *for all* $\sigma \geq \widehat{\sigma}_1^{II}$.

Total profits are increased by introducing a positive revenue share in the winner-take-all race. On the one hand, the introduction of payoff spillovers reduces firms' overinvestments in R&D. On the other hand, these payoff spillovers initially stimulate the acquisition of informative public signals, and therefore reduces the firms' underinvestment in information acquisition. Since both overinvestments in R&D and underinvestments in information acquisition are reduced, total profit is increased. For big revenue shares the free-rider incentives are dominating in the industry, and expected profits drop to zero.

7.3 Private Signal Information Acquisition

We now turn to the race where firms acquire private signals. Since signals are private, firms can no longer free-ride on each other's information acquisition investments. The first-order condition for firm i's equilibrium information acquisition investment is, after substitution of the equilibrium condition $R_i = r_i = R$, as follows:

$$\begin{aligned}\rho R \;=\;& (1-\sigma)^2 p \Big\{ \pi_i \Big(\tilde{\theta}_i(\underline{t};R), R\tilde{\theta}_j(\underline{t};R) + (1-R)\tilde{\theta}_j(\overline{t};R); \underline{\theta} \Big) \\ & - \pi_i \Big(\tilde{\theta}_i(\overline{t};R), R\tilde{\theta}_j(\underline{t};R) + (1-R)\tilde{\theta}_j(\overline{t};R); \underline{\theta} \Big) \Big\}. \qquad (35)\end{aligned}$$

Investments that obey this first-order condition trade off the marginal cost of information acquisition against its marginal revenue. The marginal revenue of information acquisition, at the right hand side of expression (35), is the expected profit gain of discovering that the cost of investment is low. The second-order condition for profit maximization can be found as expression (51) in the Appendix. The investment $\tilde{R}_i(\sigma)$ for which both the first- and second-order conditions are satisfied, is firm i's equilibrium investment.

First we analyze the firms' incentives to acquire private signals in the winner-take-all race. Since firms cannot free-ride on their rival's investment to acquire private signals, firms invest more in acquiring private signals than in acquiring public signals. This fact has a consequence for the comparison between *ex ante* expected profits. In proposition 2 (ii) we showed that for each given signal's precision, and for big enough costs of investment, firms expect higher equilibrium profits in the race with public signals than in the race with private signals. This inequality need no longer hold in the races with endogenous precisions of signals. On the one hand we have shown that generically $\hat{\Pi}_i(\hat{R}) > \tilde{\Pi}_i(\hat{R})$. But on the other hand firms invest more than $\hat{R}$ in information acquisition in the race with private signals, i.e. $\tilde{R} > \hat{R}$, which increases firm i's expected profits in the race with private signals, and therefore $\tilde{\Pi}_i(\tilde{R}) > \tilde{\Pi}_i(\hat{R})$. The sign of the difference between expected profit $\hat{\Pi}_i(\hat{R})$ and $\tilde{\Pi}_i(\tilde{R})$ is therefore ambiguous. We state these findings in proposition 8 (i).

Finally we discuss the effects of revenue sharing on the incentive to acquire private signals, and on expected profits. A change in firm i's acquired signal does not change its rival's R&D investments, since signals are private to the firms. Firm i's incentive to invest in acquiring a private signal now only depends on the appropriability of its own R&D revenue. The more revenue spills over to the rival, the less valuable its own information acquisition becomes for the firm. Therefore we observe that each firm's equilibrium information acquisition investment decreases in the revenue share σ. We state this formally in proposition 8 (ii).

The effect of a change in the revenue share on expected profits is decomposed in the following fashion:

$$\tilde{\Pi}_i'(\sigma) = \frac{\partial \tilde{\Pi}_i\left(\tilde{R}(\sigma)\middle|\sigma\right)}{\partial R} \cdot \tilde{R}'(\sigma) + \frac{\partial \tilde{\Pi}_i\left(\tilde{R}(\sigma)\middle|\sigma\right)}{\partial \sigma}, \tag{36}$$

with $\tilde{\Pi}_i(\sigma) \equiv \tilde{\Pi}_i\left(\tilde{R}(\sigma)\middle|\sigma\right)$. We know that the first term of expression (36) is negative for all revenue shares, since $\tilde{\Pi}_i(R|\sigma)$ increases in the signal's precision, while $\tilde{R}(\sigma)$ decreases in the revenue share. The second term is positive for small revenue shares, and negative for big revenue shares. These two simple observations imply that the sign of the sum of these two terms is ambiguous for small revenue shares, but definitely negative for big revenue shares. We summarize our findings in the following proposition.

Proposition 8 *Suppose that the second-order condition for information acquisition holds. (i) In the winner-take-all race ($\sigma = 0$) firms invest in equilibrium more in acquiring private than public signals: $\tilde{R}_i(0) \geq \hat{R}_i(0)$. How expected profits $\hat{\Pi}_i(\hat{R})$ and $\tilde{\Pi}_i(\tilde{R})$ compare is ambiguous. (ii) Information acquisition investments decrease in the revenue share: $\tilde{R}_i'(\sigma) < 0$ for all $\sigma \in [0,1]$. (iii) For large enough revenue shares the expected profit in the race with private signals decreases in the revenue share: there is a share $\tilde{\sigma}^I < \frac{1}{2}$ such that $\tilde{\Pi}_i'(\sigma) < 0$ for all $\sigma \geq \tilde{\sigma}^I$.*

8 Conclusion

This paper studies the interaction between the incentives to acquire and reveal information and the subsequent incentives to invest in R&D. The appropriability of the winner's revenues plays a key role in determining the incentives of firms to invest and reveal. Revenue sharing between winner and loser of the R&D race reduces overinvestments in R&D. The magnitude of the revenue spillover affects the direction into which firms would like to misrepresent their private information. Finally revenue sharing introduces two conflicting effects for the information acquisition incentives. On the one hand, revenue sharing softens free-rider effects that are due to the public good nature of information. On the other hand it weakens information acquisition incentives since the resulting expected revenues leak away to the rival.

How much information firms strategically reveal to their rival depends both on the appropriability of revenues, and on the verifiability of information. With non-verifiability information firms always have an incentive to misrepresent their private information. However if information can be costlessly verified, information disclosure only occurs for extreme revenue share. For intermediate revenue shares the "unraveling result" does not emerge. These results directly feed back in the firms' R&D incentives and their expected profits.

Although we made a substantial first step in the analysis of learning effects in R&D races, there remain some interesting extensions. For example, an analysis of welfare effects, and the effects of incomplete licensing contracts await future research.

A Appendix

In this Appendix we prove the main propositions of this paper. First we prove the lemmas on efficient and equilibrium R&D investments and profits in the race with public signals. The second subsection contains proofs of the propositions on equilibrium investments for private signals. Subsection 3 proves the propositions concerning the effects of revenue sharing. In subsection 4 we prove the lemmas and propositions concerning strategic information revelation. Finally, in subsection 5, we prove the propositions that concern strategic information acquisition.

A.1 Proof of Lemmas 1 and 2

• **Proof of Lemma 1 (Benchmark):** (i) The inequality $\overline{D}_i(\underline{t}_o;R) > \overline{D}_i(\overline{t}_o;R)$ obviously holds, since $E(\theta|\overline{t}_o;R) = \underline{\theta} + \phi(R) > \underline{\theta} = E(\theta|\underline{t}_o;R)$. (ii) The inequality $\partial\overline{D}_i(\overline{t}_o;R)/\partial R < 0$ obviously holds, since $\phi'(R) > 0$. To prove the inequality $\overline{D}_i'(R) > 0$ we note that expression (9) can be rewritten as follows:

$$\overline{D}_i'(R) = \frac{2p(1-R)\phi(R)^2 W}{(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2}, \tag{37}$$

which obviously exceeds zero. (iii) The inequality $\overline{\Pi}_i'(R) > 0$ follows immediately from the fact that $\overline{\Pi}_i(R) = \frac{1}{2}\overline{D}_i(R)W$ and $\overline{D}_i'(R) > 0$, which completes the proof. ¤

• **Proof of Lemma 2 (Public Signals):** Parts (i) and (ii) of the lemma are identical to parts (i) and (ii) in lemma 1 with 2Δ replaced by Δ. (iii) The inequality $\widehat{\Pi}_i'(R) > 0$ follows from rewriting expression (14) as follows:

$$\widehat{\Pi}_i'(R) = \frac{p(1-R)\phi(R)^2 W^2[\underline{\theta}(\underline{\theta}+\phi(R)) - \Delta(\underline{\theta}+2\Delta)]}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^3}, \tag{38}$$

which exceeds zero since

$$\underline{\theta}(\underline{\theta}+\phi(R)) - \Delta(\underline{\theta}+2\Delta) \geq \underline{\theta}^2 - \Delta(\underline{\theta}+2\Delta) = (\underline{\theta}+\Delta)(\underline{\theta}-2\Delta) > 0. \tag{39}$$

This completes the proof. ¤

A.2 Proofs for Private Signal Race

In this subsection of the Appendix we prove propositions 1 and 2.

• **Proof of Proposition 1 (Investments):** Solving equations (15) and (16) for $i,j = 1,2$ ($i \neq j$) gives the following equilibrium R&D investments with private signals for firm i:

$$\widetilde{D}_i(\underline{t};R) = \frac{(\underline{\theta}+\varphi(R)+(R-P(R))\Delta)\,W}{\widetilde{c}(R)}, \text{ and} \tag{40}$$

$$\widetilde{D}_i(\overline{t};R) = \frac{(\underline{\theta}+(R-P(R))\Delta)\,W}{\widetilde{c}(R)}, \tag{41}$$

with

$$\Omega(R) \equiv (\underline{\theta} + R\Delta)\left(\underline{\theta} + \varphi(R) + (1 - P(R))\Delta\right) - (1 - R)P(R)\Delta^2. \tag{42}$$

For the comparison of equilibrium investments in the races with public and with private signals, we observe that:

$$\begin{aligned}
\tilde{x}_i(\underline{t}; R) - \hat{x}_i(\underline{t}_o; R) &= \frac{(1 - R)\Delta\varphi(R)W}{\Omega(R)(\underline{\theta} + \Delta)} > 0, \text{ and} \\
\tilde{x}_i(\overline{t}; R) - \hat{x}_i(\overline{t}_o; R) &= \frac{\underline{\theta}[\phi(R) - \varphi(R)]W}{\Omega(R)(\underline{\theta} + \phi(R) + \Delta)} > 0.
\end{aligned}$$

The comparison of expected investments results in the following:

$$\tilde{x}_i(R) - \hat{x}_i(R) = \frac{-pR(1 - R)\phi(R)\varphi(R)(\underline{\theta} - (1 - R)\Delta)W}{\Omega(R)(\underline{\theta} + \phi(R) + \Delta)(\underline{\theta} + \Delta)} < 0.$$

It is obvious that part (i) of lemma 1 holds for $\tilde{x}_i(.; R)$. For lemma 1 (ii)'s properties we simply observe the signs of the following expressions ($i = 1, 2$):

$$\begin{aligned}
\frac{\partial \tilde{x}_i(\underline{t}; R)}{\partial R} &= \frac{-(1 - p)\Delta(\overline{\theta} + \Delta)\varphi(R)}{(1 - pR)\Omega(R)^2} < 0, \text{ and} \\
\frac{\partial \tilde{x}_i(\overline{t}; R)}{\partial R} &= \frac{-p\underline{\theta}(\underline{\theta} + \Delta)\varphi(R)}{(1 - pR)\Omega(R)^2} < 0,
\end{aligned}$$

while

$$\begin{aligned}
\tilde{x}_i'(R) &= \tilde{x}_i(\underline{t}; R) - \tilde{x}_i(\overline{t}; R) + pR\frac{\partial \tilde{x}_i(\underline{t}; R)}{\partial R} + (1 - pR)\frac{\partial \tilde{x}_i(\overline{t}; R)}{\partial R} \\
&= \frac{p\underline{\theta}\varphi(R)^2}{\Omega(R)^2} > 0.
\end{aligned}$$

This completes the proof. ¤

• **Proof of Proposition 2 (Profits): (i)** It follows directly from proposition 1 and expression (19) that $\tilde{\pi}_i(\underline{t}; R) > \hat{\pi}_i(\underline{t}_o; R)$. For a high-signal firm we analyze the profit difference:

$$\tilde{\pi}_i(\overline{t}; R) - \hat{\pi}_i(\overline{t}_o; R) = \frac{1}{2}(\underline{\theta} + \varphi(R))\tilde{x}_i(\overline{t}; R)^2 - \frac{1}{2}(\underline{\theta} + \phi(R))\hat{x}_i(\overline{t}_o; R)^2$$

$$= \frac{(\underline{\theta} + \varphi(R))(\underline{\theta} + \phi(R) + \Delta)^2(\underline{\theta} + (R - P(R))\Delta)^2 - (\underline{\theta} + \phi(R))\Omega(R)^2}{2\Omega(R)^2(\underline{\theta} + \phi(R) + \Delta)^2} \tag{43}$$

where the numerator equals:

$$\begin{aligned}
&-\varphi(R)^2(\underline{\theta}+\phi(R))(\underline{\theta}+R\Delta)^2+\varphi(R)(\underline{\theta}+(R-P(R))\Delta)^2\cdot \\
&\cdot[\phi(R)^2(\underline{\theta}+(R-P(R))\Delta)^2-\phi(R)2P(R)(\underline{\theta}+\Delta)+ \\
&-(\underline{\theta}+\Delta)(\underline{\theta}^2-(1-R-P(R))\underline{\theta}\Delta-(R-P(R))\Delta^2)]+ \\
&+\phi(R)(\underline{\theta}+(R-P(R))\Delta)(\phi(R)\underline{\theta}+(\underline{\theta}+\Delta)(\underline{\theta}-\Delta)). \qquad (44)
\end{aligned}$$

Define variable $x \equiv (1-p)(\overline{\theta}-\underline{\theta})$, and note that $\phi(R) = x/(p(1-R)^2+1-p)$, and $\varphi(R) = x/(1-pR)$. Substitution of these expressions in (43) gives the following:

$$\mathbf{e}_i(\bar{t};R)-\mathbf{b}_i(\bar{t}_o;R)=\frac{P(R)x(ax^2+bx+c)}{2(p(1-R)^2+1-p)^2(1-pR)^2\mathbf{e}(R)^2(\underline{\theta}+\phi(R)+\Delta)^2},$$

as is clear after inspection of expression (44). Since $x>0$, it suffices to show that $a,b,c>0$ for all $\underline{\theta}\geq 3\Delta$. First we show that a is positive:

$$\begin{aligned}
a &= (1-pR)[\underline{\theta}^2-(1-R)2\underline{\theta}\Delta-(1+R-R^2)\Delta^2]+(1-R)\Delta^2 \\
&> (1-R)[R^2\Delta^2+R\Delta(2\underline{\theta}-\Delta)+\underline{\theta}(\underline{\theta}-2\Delta)]>0.
\end{aligned}$$

Second we show that b is positive if $\underline{\theta}\geq 3\Delta$:

$$\begin{aligned}
b &= (2-pR(3-R))(1-pR)[(\underline{\theta}^3-2(1-R)\underline{\theta}^2\Delta-(1+2R-R^2)\underline{\theta}\Delta^2)]+ \\
&\quad +(2-pR(3-R))[2(1-R)\underline{\theta}\Delta^2-(1-p)R\Delta^3]+pR^2(1-R)(1-p)\Delta^3.
\end{aligned}$$

Since b is increasing in parameter $\underline{\theta}$, it suffices to show that b exceeds zero in $\underline{\theta}=3\Delta$, which is obvious after inspection of the following expression:

$$\begin{aligned}
b|_{\underline{\theta}=3\Delta} &= (2-pR(3-R))R[19+3R-p(7+12R+3R^2)]\Delta^3+ \\
&\quad +pR^2(1-R)(1-p)\Delta^3.
\end{aligned}$$

Finally we show that $c>0$ for all $\underline{\theta}\geq 3\Delta$:

$$\begin{aligned}
c &= (p(1-R)^2+1-p)(\underline{\theta}+\Delta)[(1-pR)\underline{\theta}+(1-p)R\Delta]\cdot c_0(\underline{\theta}), \text{ with} \\
c_0(\underline{\theta}) &\equiv [(1-pR)\underline{\theta}^2-(3-R-2pR(2-R))\underline{\theta}\Delta-(1-p)R\Delta^2].
\end{aligned}$$

Since $c_0(\underline{\theta})$ increases in $\underline{\theta}$, we complete the proof of part (i) by observing that:

$$c_0(\underline{\theta})\geq c_0(3\Delta)=2R[(1+p(2-3R)]\Delta^2>0.$$

Since $x > 0$ and $a, b, c > 0$ for all $\underline{\theta} \geq 3\Delta$, we conclude that $\widetilde{\pi}_i(\bar{t}; R) > \widehat{\pi}_i(\bar{t}_o; R)$ for all $\underline{\theta} \geq 3\Delta$.

(ii) The proof is similar to part (i). We can rewrite the profit difference with public and private signals as follows:

$$\widehat{\Pi}_i(R) - \widetilde{\Pi}_i(R) = \frac{P(R)x^2(Ax^2 + Bx + C)}{2(p(1-R)^2 + 1 - p)^2(1 - pR)\widetilde{\alpha}(R)^2(\underline{\theta} + \Delta)(\underline{\theta} + \phi(R) + \Delta)^2}.$$

(ii.a) Note that for $\overline{\theta}$ sufficiently small x is approximately zero. In that case the sign of $\widehat{\Pi}_i(R) - \widetilde{\Pi}_i(R)$ is determined by the sign of C. We can rewrite C as follows:

$$\begin{aligned} C &= [p(1-R)^2 + 1 - p](\underline{\theta} + \Delta)^2 \cdot C_1(p), \text{ with} \\ C_1(p, R) &\equiv (1 - pR)\underline{\theta}^2(\underline{\theta} - 2(2-R)\Delta) + \\ &\quad +(1 - (5-3p)R + R^2)\underline{\theta}\Delta^2 + 2(1-p)R(1-R)\Delta^3. \end{aligned}$$

Notice that for $R = 0$ and $R = 1$, respectively, we obtain the following:

$$\begin{aligned} C_1(p, 0) &\equiv \underline{\theta}(\underline{\theta} - 4\underline{\theta}\Delta + \Delta^2) < 0, \text{ for all } \underline{\theta} < (2 + \sqrt{3})\Delta, \\ C_1(p, 1) &\equiv (1-p)\underline{\theta}(\underline{\theta} + \Delta)(\underline{\theta} - 3\Delta) > 0, \text{ for all } \underline{\theta} > 3\Delta. \end{aligned}$$

Since $C_1(p, R)$ is continuous in R, critical values R' and R'' exist, which proves part (ii.a) of the proposition.

(ii.b) For part (ii.b) it suffices to show that $A, B, C > 0$ for all $\underline{\theta} \geq (2+\sqrt{3})\Delta$, since $x > 0$. First we show that $A > 0$:

$$A \equiv \underline{\theta}[\Delta^2 R^2 + \Delta(2\underline{\theta} - \Delta)R + \underline{\theta}^2 - 2\underline{\theta}\Delta - \Delta^2] > 0, \text{ for all } \underline{\theta} \geq 3\Delta,$$

and therefore certainly for all $\underline{\theta} \geq (2+\sqrt{3})\Delta$. Second we can write coefficient B as follows:

$$\begin{aligned} B \;\equiv\; & (\underline{\theta} + \Delta)\{pR(1-R)[(3-R)\underline{\theta} - (1-R)\Delta]\Delta^2 + \\ & +[2 - pR(3-R)](\underline{\theta}^3 - (3-2R)\Delta\underline{\theta}^2 - R(3-R)\Delta^3\underline{\theta} + R(1-R)\Delta^3)\}, \end{aligned}$$

Since B is linear in parameter p, it suffices to show that $B > 0$ for $p \in \{0, 1\}$, for showing that B is positive for all p. If $p = 0$, B equals:

$$\begin{aligned} B|_{p=0} &= 2(\underline{\theta} + \Delta)[\underline{\theta}^3 - (3-2R)\Delta\underline{\theta}^2 - R(3-R)\Delta^3\underline{\theta} + R(1-R)\Delta^3] \\ &= 2(\underline{\theta} + \Delta)[(2\underline{\theta} - (1-R)\Delta)(\underline{\theta} - \Delta)R\Delta + \underline{\theta}^2(\underline{\theta} - 3\Delta) > 0, \end{aligned}$$

for all $\underline{\theta} \geq 3\Delta$. If $p = 1$, B equals:

$$\begin{aligned}
B|_{p=1} &= (\underline{\theta} + \Delta)(1 - R) \cdot B_1(R), \text{ with} \\
B_1(R) &\equiv 2\underline{\theta}^2(\underline{\theta} - 3\Delta) - R(\underline{\theta}^3 - 7\underline{\theta}^2\Delta + 3\underline{\theta}\Delta^2 - \Delta^3) + \\
&\quad -R^2\Delta(\underline{\theta} - \Delta)[2\underline{\theta} - (2 - R)\Delta],
\end{aligned}$$

which is concave in R. Note that if $\underline{\theta} \geq 3\Delta$, $B_1(0) = 2\underline{\theta}^2(\underline{\theta} - 3\Delta) > 0$, and $B_1(1) = \underline{\theta}^2(\underline{\theta} - \Delta) > 0$, and since $B_1(R)$ is concave in R, $B|_{p=1} > 0$ for all R, if $\underline{\theta} \geq 3\Delta$. This establishes that if $\underline{\theta} \geq 3\Delta$, $B > 0$. Third we need to show that if $\underline{\theta} \geq (2 + \sqrt{3})\Delta$, then $C > 0$. Notice that $C_1(p, R)$ is linear in p, with

$$\begin{aligned}
C_1(0, R) &= R\Delta(\underline{\theta} - 2\Delta)[2\underline{\theta} - (1 - R)\Delta] + \underline{\theta}(\underline{\theta}^2 - 4\underline{\theta}\Delta + \Delta^2), \text{ and} \\
C_1(1, R) &= \underline{\theta}(1 - R)[R\Delta(2\underline{\theta} - \Delta) + \underline{\theta}^2 - 4\underline{\theta}\Delta + \Delta^2].
\end{aligned}$$

If $\underline{\theta} \geq (2 + \sqrt{3})\Delta$, then $\underline{\theta}^2 - 4\underline{\theta}\Delta + \Delta^2 > 0$, and consequently $C_1(p, R) > 0$ and $C > 0$. This completes the proof of part (ii.b) of the proposition.
(iii) Finally we show that if $\underline{\theta} \geq 3\Delta$, $\hat{\Pi}_i(R)$ increases in R, as in lemma 1 (iii), by observing that:

$$\hat{\Pi}_i'(R) = \frac{p\underline{\theta}\varphi(R)^2 \cdot g(\overline{\theta})}{(1 - pR)\epsilon(R)^3},$$

with

$$\begin{aligned}
g(\overline{\theta}) &\equiv (1 - p)(\underline{\theta} - R\Delta)\overline{\theta} + p[(1 - R)\underline{\theta}^2 + R\Delta(\underline{\theta} + 3\Delta)] - (\underline{\theta} + 3R\Delta)\Delta \\
&> g(\underline{\theta}) = (\underline{\theta} - \Delta)\underline{\theta} - R\Delta(\underline{\theta} + 3\Delta) - pR(\underline{\theta} + \Delta)(\underline{\theta} - 3\Delta) \\
&\geq (1 - R)\underline{\theta}(\underline{\theta} - \Delta), \text{ for all } \underline{\theta} \geq 3\Delta.
\end{aligned}$$

Since for all $\underline{\theta} \geq 3\Delta$: $g(\overline{\theta}) > g(\underline{\theta}) > 0$, we obtain that $\hat{\Pi}_i'(R) > 0$, for all $\underline{\theta} \geq 3\Delta$. This proves the proposition. ¤

A.3 Proofs for Revenue Sharing

In this subsection of the Appendix we prove propositions 3 and 4.

• **Proof of Proposition 3 (Interim): (i)** The fact that equilibrium investments decrease in the revenue share follows obviously from expression (23).

(ii) The derivative of the equilibrium *interim* profits with respect to the revenue share σ is linear in σ. This is clear after differentiating expression (24) with respect to σ:

$$\frac{\partial \pi_i(.|\sigma)}{\partial \sigma} = (1-2\sigma)(WD_j(.) - \pi_i(.)) - \pi_i(.).$$

Initially expected *interim* profits increase in σ, i.e. $\partial\pi_i(.|0)/\partial\sigma = WD_j(.) - 2\pi_i(.) > 0$, since with public signals we obtain:

$$\frac{\partial \hat{\pi}_i(.|0)}{\partial \sigma} = W\hat{D}_j(.) - 2\hat{\pi}_i(.) = \frac{W^2}{E(\theta|.)+\Delta}\left(1 - \frac{E(\theta|.)}{E(\theta|.)+\Delta}\right) > 0,$$

and with private signals we obtain:

$$\begin{aligned}
\frac{\partial \tilde{\pi}_i(\underline{t};R|0)}{\partial \sigma} &= \tilde{D}_j(\underline{t};R)\left(W - \underline{\theta}\tilde{D}_i(\underline{t};R)\right) = \frac{\tilde{D}_j(\underline{t};R)W}{\tilde{n}(R)} \cdot \tilde{\gamma}_0(R), \\
\text{with } \tilde{\gamma}_0(R) &\equiv \tilde{n}(R) - \underline{\theta}[\underline{\theta} + \varphi(R) + (R - P(R))\Delta] \\
&= \Delta(R[\underline{\theta} + \varphi(R) + (1-P(R))\Delta] + (1-R)[\underline{\theta} - P(R)\Delta]) > 0,
\end{aligned}$$

and

$$\begin{aligned}
\frac{\partial \tilde{\pi}_i(\bar{t};R|0)}{\partial \sigma} &= \tilde{D}_j(\bar{t};R)\left(W - (\underline{\theta} + \varphi(R))\tilde{D}_i(\bar{t};R)\right) = \frac{\tilde{D}_j(\bar{t};R)W}{\tilde{n}(R)} \cdot \tilde{\gamma}_1(R), \\
\text{with } \tilde{\gamma}_1(R) &\equiv \tilde{n}(R) - (\underline{\theta} + \varphi(R))[\underline{\theta} + (R - P(R))\Delta] \\
&= \Delta(P(R)[\underline{\theta} + \varphi(R) - (1-R)\Delta] + (1-P(R))[\underline{\theta} + R\Delta]) > 0,
\end{aligned}$$

with $\tilde{n}(R)$ as in (42). It is clear that for $\sigma = \frac{1}{2}$ equilibrium profits are decreasing in σ: $\partial\pi_i(.|\frac{1}{2})/\partial\sigma = -\pi_i(.) < 0$. Since $\partial\pi_i(.|\sigma)/\partial\sigma$ is linear in σ, this gives the existence of critical share $\sigma' \in (0, \frac{1}{2})$. This completes the proof. ¤

• **Proof of Proposition 4 (Ex Ante): (i)** This follows clearly from expression (26).

(ii.a) We evaluate the difference in expected efficient profits and maximal expected equilibrium profits for firms with public signals. The profit difference is as follows:

$$\overline{\Pi}_i(R) - \hat{\Pi}_i(R|\hat{\sigma}(R)) = \frac{2W\overline{D}_i(R)\left(\hat{D}_j(R)W - \hat{\Pi}_i(R)\right) - \hat{D}_j(R)^2W^2}{4\left(\hat{D}_j(R)W - \hat{\Pi}_i(R)\right)}, \quad (45)$$

where the numerator equals:

$$
\begin{aligned}
& \hat{D}_j(R)W^2 \left(2\overline{D}_i(R) - \hat{D}_j(R)\right) - 2W\overline{D}_i(R)\hat{\Pi}_i(R) \\
= \; & W^4 \left(E\left\{\frac{1}{\theta+\Delta}\right\} E\left\{\frac{\theta}{(\theta+2\Delta)(\theta+\Delta)}\right\} - E\left\{\frac{1}{\theta+2\Delta}\right\} E\left\{\frac{\theta}{(\theta+\Delta)^2}\right\}\right) \\
= \; & W^4 \frac{\underline{\theta}+q\phi(R)+\Delta}{(\underline{\theta}+\Delta)(\underline{\theta}+\phi(R)+\Delta)} \cdot \\
& \cdot \left(\frac{q\underline{\theta}}{(\underline{\theta}+2\Delta)(\underline{\theta}+\Delta)} + \frac{(1-q)(\underline{\theta}+\phi(R))}{(\underline{\theta}+\phi(R)+2\Delta)(\underline{\theta}+\phi(R)+\Delta)} \right) + \\
& -W^4 \frac{\underline{\theta}+q\phi(R)+2\Delta}{(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)} \left(\frac{q\underline{\theta}}{(\underline{\theta}+\Delta)^2} + \frac{(1-q)(\underline{\theta}+\phi(R))}{(\underline{\theta}+\phi(R)+\Delta)^2} \right) \\
= \; & \frac{q(1-q)(p(1-R)^2+1-p)\phi(R)^2\Delta^2W^4}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)} > 0, \text{ with}
\end{aligned}
$$

$q \equiv p(1-(1-R)^2)$. Second we show that efficient expected profits exceed maximal expected profits of firms with private signals. The difference between the expected efficient profit and the maximal expected equilibrium profit with private signals, $\overline{\Pi}_i(R) - \tilde{\Pi}_i(R|\tilde{e}(R))$, is similar to expression (45) with $\hat{D}_j(R)$ (resp. $\hat{\Pi}_i(R)$) replaced by $\tilde{D}_j(R)$ (resp. $\tilde{\Pi}_i(R)$). We rewrite the numerator of this expression, with $\tilde{e}(R)$ as defined in (42), as follows:

$$
\begin{aligned}
& (\underline{\theta}+\phi(R)+2\Delta)(\underline{\theta}+2\Delta)\tilde{e}(R)^2 \left(\tilde{D}_j(R)W - \tilde{\Pi}_i(R)\right)\left(\overline{\Pi}_i(R) - \tilde{\Pi}_i(R|\tilde{e}(R))\right) \\
= \; & W^4(\underline{\theta}+(2-R)pR\phi(R)+2\Delta)[2\tilde{e}(R)(\underline{\theta}+pR\varphi(R)+(R-P(R))\Delta) \\
& -(\underline{\theta}+\varphi(R))(\underline{\theta}+(R-P(R))\Delta)^2 - pR\varphi(R)(\underline{\theta}(\underline{\theta}+\varphi(R)) - (R-P(R))^2\Delta^2)] \\
& -W^4(\underline{\theta}+\phi(R)+2\Delta)(\underline{\theta}+2\Delta)(\underline{\theta}+pR\varphi(R)+(R-P(R))\Delta)^2 \\
= \; & pR\varphi(R)\phi(R)W^4[P(R)(\underline{\theta}-2(1-R)\Delta)(1-p)(\overline{\theta}-\underline{\theta}) + \\
& +(1-R)(\underline{\theta}-2(1-R)\Delta)\underline{\theta} + (1-p)(2-R)(R-P(R))R\Delta^2],
\end{aligned}
$$

which obviously exceeds zero for all R.

(ii.b) To prove part (b) we need to show that if $\underline{\theta} \geq 3\Delta$, $\hat{\Pi}_i(R|\hat{b}(R)) - \tilde{\Pi}_i(R|\tilde{e}(R)) > 0$. This expected profit difference equals:

$$
\hat{\Pi}_i(R|\hat{b}(R)) - \tilde{\Pi}_i(R|\tilde{e}(R)) = W^2 \frac{\hat{D}_j(R)^2\left(\tilde{D}_j(R)W - \tilde{\Pi}_i(R)\right) - \tilde{D}_j(R)^2\left(\hat{D}_j(R)W - \hat{\Pi}_i(R)\right)}{4\left(\hat{D}_j(R)W - \hat{\Pi}_i(R)\right)\left(\tilde{D}_j(R)W - \tilde{\Pi}_i(R)\right)}
$$

The numerator of this expression can be rewritten to:

$$\widehat{D}_j(R)^2\left(\widetilde{D}_j(R)W - \widetilde{\Pi}_i(R)\right) - \widetilde{D}_j(R)^2\left(\widehat{D}_j(R)W - \widehat{\Pi}_i(R)\right) = \frac{P(R)y^2(\alpha y^2 + \beta y + \gamma)}{2(p(1-R)^2+1-p)^2(1-pR)(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2\widetilde{\sigma}(R)^2},$$

where $y \equiv pR(1-p)(\overline{\theta}-\underline{\theta})$ and

$$\begin{aligned}
\alpha &\equiv (2-R)(\underline{\theta}-2(1-R)\Delta) > 0,\\
\beta &\equiv (3-R)(\underline{\theta}-2(1-R)\Delta)\underline{\theta} - (1-R)(1+2R-R^2)\Delta^2 + \\
&\quad -2pR(2-R)[\underline{\theta}^2 - (1-R)(2\underline{\theta}+\Delta)\Delta]\\
&> (1-R)[(3-2R)(\underline{\theta}-2(1-R)\Delta)\underline{\theta} - (1-R)^2\Delta^2], \text{ if } \underline{\theta} \geq 3\Delta\\
&> (1-R)(8+14R-13R^2) > 0, \text{ if } \underline{\theta} \geq 3\Delta\\
\gamma &\equiv (p(1-R)^2+1-p)[(\underline{\theta}-2(1-R)\Delta)\underline{\theta} + (1+R-R^2)\Delta^2 + \\
&\quad -pR(\underline{\theta}+\Delta)(\underline{\theta}-(3-2R)\Delta)\\
&> (1-R)[\underline{\theta}^2 - (1-R)(2\underline{\theta}+\Delta)\Delta] > 0, \text{ if } \underline{\theta} \geq 3\Delta.
\end{aligned}$$

Since $\alpha, \beta, \gamma > 0$ if $\underline{\theta} \geq 3\Delta$,and $y > 0$, we obtain $\widehat{\Pi}_i(R|\widehat{\sigma}(R)) > \widetilde{\Pi}_i(R|\widetilde{\sigma}(R))$ for all R, if $\underline{\theta} \geq 3\Delta$.

(iii) We prove property (iii) of lemma 1 by observing that if $\underline{\theta} \geq 3\Delta$, then both *ex ante* expected "winner-take-all" investments and profits increase in the signal's precision, R, as shown in lemma 2 and propositions 1 and 2. This completes the proof. ¤

A.4 Proofs for Strategic Revelation

In this subsection we prove proposition 5, lemma 3, and proposition 6.

• **Proof of Proposition 5 (No Complete Revelation):** Suppose complete revelation does happen in equilibrium. Then equilibrium beliefs are such that any statement is believed. Firm j's equilibrium investments would be $\widehat{D}_j(\underline{t}_o; R|\sigma)$ and $\widehat{D}_j(\overline{t}_o; R|\sigma)$, respectively. Suppose that firm j fully reveals his information, and that he received signal $t_j = \overline{t}$. Then if firm i received signal $\underline{t}$ and reveals it, firms invest $\widehat{D}(\underline{t}_o; R|\sigma)$, and firm i has expected profit:

$$\pi_i(\underline{t}|\underline{t}) = (1-\sigma)W^2\frac{(1-\sigma)\frac{1}{2}\underline{\theta} + \sigma(\underline{\theta}+\Delta)}{(\underline{\theta}+\Delta)^2}.$$

If firm i states $\overline{t}$ instead, this makes firm j invest $\text{Þ}_j(\overline{t}_o; R|\sigma)$. Firm i's optimal response to $\text{Þ}_j(\overline{t}_o; R|\sigma)$ is $(\underline{\theta} + \phi(R))\text{Þ}_j(\overline{t}_o; R|\sigma)/\underline{\theta}$. Firm i's profit from overstating his signal is consequently:

$$\pi_i(\overline{t}|\underline{t}) = (1-\sigma)W^2 \frac{(1-\sigma)\frac{1}{2}(\underline{\theta}+\phi(R))^2 + \sigma\underline{\theta}(\underline{\theta}+\phi(R)+\Delta)}{\underline{\theta}(\underline{\theta}+\phi(R)+\Delta)^2}.$$

The difference in profit between overstating and truth-telling is:

$$\pi_i(\overline{t}|\underline{t}) - \pi_i(\underline{t}|\underline{t}) = \frac{(1-\sigma)W^2\left((1-\sigma)\kappa + \sigma(-\lambda)\right)}{\underline{\theta}(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2},$$

with

$$\begin{aligned}
\kappa &\equiv \frac{1}{2}\left([(\underline{\theta}+\phi(R))(\underline{\theta}+\Delta)]^2 - [\underline{\theta}(\underline{\theta}+\phi(R)+\Delta)]^2\right), \\
\lambda &\equiv \underline{\theta}(\underline{\theta}+\Delta)(\underline{\theta}+\phi(R)+\Delta)\phi(R).
\end{aligned}$$

Hence, there is a $\overline{\sigma} \in (0,1)$ such that $\pi_i(\overline{t}|\underline{t}) > \pi_i(\underline{t}|\underline{t})$ iff $\sigma < \overline{\sigma}$. Similar for a $\overline{t}$-firm i, stating $\underline{t}$ (resp. $\overline{t}$) makes $\overline{t}$-firm j choose $\text{Þ}_j(\underline{t}_o; R|\sigma)$ (resp. $\text{Þ}_j(\overline{t}_o; R|\sigma)$). Firm i's optimal response to this investment is $\underline{\theta}\text{Þ}_i(\underline{t}_o; R|\sigma)/(\underline{\theta}+\phi(R))$ (resp. $\text{Þ}_i(\overline{t}_o; R|\sigma)$). Firm i's profit for understating his signal is:

$$\pi_i(\underline{t}|\overline{t}) = (1-\sigma)W^2 \frac{(1-\sigma)\frac{1}{2}\underline{\theta}^2 + \sigma(\underline{\theta}+\Delta)(\underline{\theta}+\phi(R))}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R))},$$

while truth-telling gives the firm:

$$\pi_i(\overline{t}|\overline{t}) = (1-\sigma)W^2 \frac{(1-\sigma)\frac{1}{2}(\underline{\theta}+\phi(R)) + \sigma(\underline{\theta}+\phi(r)+\Delta)}{(\underline{\theta}+\phi(R)+\Delta)^2}.$$

The difference in profit between understating and truth-telling is:

$$\pi_i(\underline{t}|\overline{t}) - \pi_i(\overline{t}|\overline{t}) = \frac{(1-\sigma)W^2\left((1-\sigma)(-\kappa) + \sigma\Lambda\right)}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2(\underline{\theta}+\phi(R))},$$

with

$$\Lambda \equiv (\underline{\theta}+\phi(R))(\underline{\theta}+\Delta)(\underline{\theta}+\phi(R)+\Delta)\phi(R).$$

Hence, there is a $\underline{\sigma} \in (0,1)$ such that $\pi_i(\underline{t}|\overline{t}) \geq \pi_i(\overline{t}|\overline{t})$ iff $\sigma \geq \underline{\sigma}$. Since $\phi(R) > 0$, we obtain that $\lambda < \Lambda$. This implies that $\underline{\sigma} < \overline{\sigma}$, and, thus, is deviating from complete revelation profitable for all $\sigma \in [0,1]$. This completes the proof. ¤

• **Proof of Lemma 3 (No Revelation):** Observe that if firms never update their beliefs, each firm is indifferent between all revelation rules, i.e. $\pi_i(\tau_i(t_i),\tau_j) = \pi_i(\tau_i'(t_i),\tau_j) = E_\theta\left[\pi_i(\hat{\theta};\theta)|t_i;R\right]$ for all τ_i,τ_i' and τ_j. No revelation, e.g. $\tau_i(t_i) = \underline{t}$ for all $t_i \in \{\underline{t},\overline{t}\}$ with $i = 1,2$, is therefore weakly preferred by firms, which is consistent with beliefs. For $\sigma < \underline{\sigma}$ and $\sigma > \overline{\sigma}$ there are more out-of-equilibrium beliefs that support non-revelation as an equilibrium strategy. For example it is easy to verify that, if $\sigma < \underline{\sigma}$ (resp. $\sigma > \overline{\sigma}$), the skeptical out-of-equilibrium belief that assigns probability 1 to signal $\underline{t}$ (resp. $\overline{t}$) after a deviation implements the non-informative equilibrium. This completes the proof. ¤

• **Proof of Proposition 6 (Verifiable Information):** If only one type of firm chooses to conceal its signal, its rival can infer its information perfectly. We therefore only need to distinguish between strategies of full disclosure and full concealment. We take $\underline{\sigma}$, $\overline{\sigma}$, and $\pi_i(.|.)$ as in the proof to proposition 5, and characterize part (i), (ii) and (iii), respectively.

(i) Take $\sigma \leq \underline{\sigma}$. Suppose that firm j discloses its information: $\tau_j(t_j) = t_j$ for $t_j \in \{\underline{t},\overline{t}\}$. In that case firm i's disclosure rule can only affect the equilibrium outcome if firm j discloses $\overline{t}$. Firm i's expected profit from disclosing private signals $\underline{t}$ and $\overline{t}$ is then $\pi_i(\underline{t}|\underline{t})$ and $\pi_i(\overline{t}|\overline{t})$, respectively. Suppose that firm i deviates from complete revelation and conceals its signal. After concealment firm j updates its beliefs skeptically, and believes that $t_i = \underline{t}$ with probability 1, i.e. $\pi_i(\varnothing|t_i) \equiv \pi_i(\underline{t}|t_i)$. Consequently it invests $\hat{\theta}_j(\underline{t}_o; R|\sigma)$ in R&D. This leaves firm i indifferent between disclosing and concealing when $t_i = \underline{t}$. If firm i has private signal $\overline{t}$, it prefers to disclose its signal, since $\pi_i(\overline{t}|\overline{t}) \geq \pi_i(\underline{t}|\overline{t})$ iff $\sigma \leq \underline{\sigma}$. Hence sceptical beliefs are consistent with firm's incentives, and firms' disclosure strategies are optimal given beliefs.

(ii) Take $\underline{\sigma} < \sigma < \overline{\sigma}$, and suppose that firm j discloses its information. Firm j's investments can only be affected by firm i's disclosure decision when firm j receives a bad signal, $t_j = \overline{t}$. We consider this case. After firm i's concealment, $\hat{t}_i = \varnothing$, firm j assigns probability μ to the contingency that firm i received a good signal, $t_i = \underline{t}$, with $0 \leq \mu \leq 1$. Firm j's expected costs of investment after concealment are $\underline{\theta} + (1-\mu)\phi(R)$. The first-order condition for firm j's investments is as follows:

$$(\underline{\theta} + (1-\mu)\phi(R))D_j(\varnothing; R) = (1-\sigma)W - \left(\mu D_i(\underline{t}) + (1-\mu)D_i(\bar{t})\right)\Delta.$$

Firm i's first-order conditions remain unchanged. Given firm j's belief, we obtain the following equilibrium investments:

$$\begin{aligned}
D_j^{\mu}(\varnothing; R|\sigma) &= \frac{(1-\sigma)W}{N_{\mu}}\left[\underline{\theta}(\underline{\theta} + \phi(R)) - (\underline{\theta} + \mu\phi(R))\Delta\right], \\
D_i^{\mu}(\underline{t}; R|\sigma) &= \frac{(1-\sigma)W}{N_{\mu}}(\underline{\theta} + \phi(R))(\underline{\theta} + (1-\mu)\phi(R) - \Delta), \\
D_i^{\mu}(\bar{t}; R|\sigma) &= \frac{(1-\sigma)W}{N_{\mu}}\underline{\theta}(\underline{\theta} + (1-\mu)\phi(R) - \Delta),
\end{aligned}$$

with

$$N_{\mu} \equiv \underline{\theta}(\underline{\theta} + \phi(R))(\underline{\theta} + (1-\mu)\phi(R)) - (\underline{\theta} + \mu\phi(R))\Delta^2.$$

Firm i's expected equilibrium profits are:

$$\begin{aligned}
\pi_i^{\mu}(\varnothing|\underline{t}) &= \frac{1}{2}\underline{\theta}D_i^{\mu}(\underline{t}; R|\sigma)^2 + \sigma W D_j^{\mu}(\varnothing; R|\sigma) \\
\pi_i^{\mu}(\varnothing|\bar{t}) &= \frac{1}{2}(\underline{\theta} + \phi(R))D_i^{\mu}(\bar{t}; R|\sigma)^2 + \sigma W D_j^{\mu}(\varnothing; R|\sigma).
\end{aligned}$$

Note that for belief $\mu = 0$ firm i strictly prefers to conceal $\underline{t}$, since $\pi_i^0(\varnothing|\underline{t}) = \pi_i(\bar{t}|\underline{t}) > \pi_i(\underline{t}|\underline{t})$ for $\sigma < \bar{\sigma}$. We can therefore rule out belief $\mu = 0$ as supporting a full disclosure equilibrium. Belief $\mu = 1$ can be ruled out too, because firm i prefers to conceal a bad signal given this belief, i.e. $\pi_i^1(\varnothing|\bar{t}) = \pi_i(\underline{t}|\bar{t}) > \pi_i(\bar{t}|\bar{t})$ for $\sigma > \underline{\sigma}$. For beliefs strictly between 0 and 1 there is a critical value $\bar{\sigma}^{\mu}$ (resp. $\underline{\sigma}^{\mu}$) such that disclosing $\underline{t}$ (resp. $\bar{t}$) is profitable for firm i iff $\sigma \geq \bar{\sigma}^{\mu}$ (resp. $\sigma \leq \underline{\sigma}^{\mu}$). The critical values are defined as follows:

$$\begin{aligned}
\underline{\sigma}^{\mu} &= \frac{\underline{\theta} + \phi(R)}{2n_{\mu}(\bar{t})}\left[d_i^{\mu}(\bar{t}; R)^2 - \hat{d}_i(\bar{t}; R)^2\right], \text{ and} \\
\bar{\sigma}^{\mu} &= \frac{\underline{\theta}}{2n_{\mu}(\bar{t})}\left[d_i^{\mu}(\underline{t}; R)^2 - \hat{d}_i(\underline{t}; R)^2\right],
\end{aligned}$$

where

$$n_\mu(t_i) \equiv \frac{1}{2}E(\theta|t_i,\bar{t})\left(d_i^\mu(t_i;R)^2 - \hat{d}_i(t_i;R)^2\right) - \left(d_j^\mu(\varnothing;R) - \hat{d}_j(t_i;R)\right),$$

for $t_i \in \{\underline{t},\bar{t}\}$ and $i,j=1,2,\ i\neq j$, and $d_\ell(.) \equiv D_\ell(.)/(1-\sigma)W$, with $\ell = i,j$. For revenue share σ and belief μ full disclosure is an equilibrium strategy, iff $\overline{\sigma}^\mu \leq \sigma \leq \underline{\sigma}^\mu$. First we verify that both $\underline{\sigma}^\mu$ and $\overline{\sigma}^\mu$ are monotonically decreasing in belief μ for $0<\mu<1$. Define:

$$\begin{aligned} m_\mu(t_i) \quad \equiv \quad & \frac{1}{2}\frac{\partial d_j^\mu(\varnothing;R)}{\partial\mu}\left(d_i^\mu(t_i;R)^2 - \hat{d}_i(t_i;R)^2\right) + \\ & -d_i^\mu(t_i;R)\frac{\partial d_i^\mu(t_i;R)}{\partial\mu}\left(d_j^\mu(\varnothing;R) - \hat{d}_j(t_i;R)\right), \end{aligned}$$

for $t_i \in \{\underline{t},\bar{t}\}$ and $i,j=1,2,\ i\neq j$. Differentiation of $\underline{\sigma}^\mu$ and $\overline{\sigma}^\mu$ results in the following:

$$\begin{aligned} \frac{\partial\underline{\sigma}^\mu}{\partial\mu} &= \frac{(\underline{\theta}+\phi(R))m_\mu(\bar{t})}{n_\mu(\bar{t})^2} = \frac{-\mu^2\frac{1}{2}\underline{\theta}\phi(R)^3\Delta^2(\underline{\theta}+\phi(R))(\underline{\theta}+\phi(R)-\Delta)(\underline{\theta}-\Delta)^3}{(\underline{\theta}+\phi(R)+\Delta)^2 n_\mu(\bar{t})^2 N_\mu^4}, \\ \frac{\partial\overline{\sigma}^\mu}{\partial\mu} &= \frac{\underline{\theta}m_\mu(\underline{t})}{n_\mu(\underline{t})^2} = \frac{-(1-\mu)^2\frac{1}{2}\underline{\theta}^2\phi(R)^3\Delta^2(\underline{\theta}+\phi(R))(\underline{\theta}+\phi(R)-\Delta)^3(\underline{\theta}-\Delta)}{(\underline{\theta}+\Delta)^2 n_\mu(\underline{t})^2 N_\mu^4}. \end{aligned}$$

These expressions are clearly non-positive. Furthermore, it is easily verified that:

$$\lim_{\mu\downarrow 0}\underline{\sigma}^\mu = \frac{\Delta}{\underline{\theta}+\phi(R)+2\Delta} < \frac{\Delta}{\underline{\theta}+2\Delta} = \lim_{\mu\uparrow 1}\overline{\sigma}^\mu.$$

In combination with monotonicity this implies that $\underline{\sigma}^\mu < \overline{\sigma}^\mu$ for all $0<\mu<1$. Therefore there is no belief μ such that full disclosure is chosen in equilibrium.
(iii) For $\sigma \geq \overline{\sigma}$ we have a similar argument as in (i). Sceptical beliefs after concealment are to believe that your rival has a "bad" signal, i.e. $\pi_i(\varnothing|t_i) \equiv \pi_i(\bar{t}|t_i)$. This leaves firm i with a bad signal indifferent between disclosing and concealing. Firm i with a good signal is worse off by concealing his signal, since $\pi_i(\bar{t}|\underline{t}) \leq \pi_i(\underline{t}|\underline{t})$ iff $\sigma \geq \overline{\sigma}$. This completes the proof. ¤

A.5 Proofs for Information Acquisition

In this subsection we prove propositions 7 and 8.

• **Efficient Information Acquisition:** When firms choose information acquisition investments that maximize their joint expected profits, firm i's efficient R&D investment $\overline{D}_i^I(t_o; R_i, R_j)$ equals (6) with $\phi(R)$ replaced by:

$$\phi^I(R_i, R_j) \equiv \frac{(1-p)(\overline{\theta}-\underline{\theta})}{p(1-R_i)(1-R_j)+1-p}. \tag{46}$$

Notice that $\phi^I(R, R) = \phi(R)$. Given these efficient R&D investments, each firm chooses its information acquisition investments to maximize the sum of the firms' *ex ante* expected profits, i.e. firms maximize:

$$[p(1-R_i)(1-R_j)+1-p]\sum_{\ell=1}\pi_\ell\left(\overline{D}^I(\bar{t}_o; R_i, R_j); \underline{\theta}+\phi^I(R_i, R_j)\right) +$$
$$+p[1-(1-R_i)(1-R_j)]\sum_{\ell=1}\pi_\ell\left(\overline{D}^I(\underline{t}_o; R_i, R_j); \underline{\theta}\right) - \frac{1}{2}\rho\sum_{\ell=1}R_\ell^2,$$

which results in first-order condition (29).

• **Proof of Proposition 7:** Firm i's equilibrium R&D investments in the race with public signals, given two bad signals, are as follows:

$$\widehat{D}_i^I(\bar{t}_o; R_i|\sigma) = \widehat{D}_i(\bar{t}_o; r|\sigma)\frac{\underline{\theta}+\phi(r)}{\underline{\theta}+\phi^I(R_i, r_j)}.$$

The firm's expected profits given equilibrium R&D investments are as follows:

$$[p(1-R_i)(1-R_j)+1-p]\pi_i\left(\widehat{D}_i^I(\bar{t}_o; R_i|\sigma), \widehat{D}_j^I(\bar{t}_o; r_j|\sigma); \underline{\theta}+\phi^I(R_i, R_j)\Big|\sigma\right) +$$
$$+p[1-(1-R_i)(1-R_j)]\pi_i\left(\widehat{D}^I(\underline{t}_o; R_i|\sigma); \underline{\theta}\Big|\sigma\right) - \frac{1}{2}\rho R_i^2. \tag{47}$$

The first-order condition of profit maximization is stated in expression (30), and the second-order condition is as follows:

$$\rho \geq -(1-\sigma)^2 p(1-R)\frac{\partial\pi_i\left(\widehat{D}^I(\bar{t}_o; R); \underline{\theta}\right)}{\partial R_i}. \tag{48}$$

(i) First-order condition (29) for efficient information acquisition reduces to:

$$\rho R = \frac{p(1-R)\phi(R)^2W^2}{(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2}. \tag{49}$$

The winner-take-all marginal revenue of acquiring a public signal is maximally:

$$
\begin{aligned}
\widehat{MR}(R) &= p(1-R)\left\{\frac{1}{2}\underline{\theta}\,\hat{b}_i(\underline{t}_o;R)^2-\left(\frac{1}{2}\underline{\theta}+\phi(R)\right)\hat{b}_i(\bar{t}_o;R)^2\right\}\\
&= \frac{p(1-R)\phi(R)\left(\frac{1}{2}\underline{\theta}\phi(R)-(\underline{\theta}+\Delta)\Delta\right)W^2}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2}.
\end{aligned}
$$

First we show that marginal revenues of efficient information acquisition investments are strictly larger than those in the public signal race:

$$
\frac{p(1-R)\phi(R)^2W^2}{(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2}>\frac{p(1-R)\phi(R)\left(\frac{1}{2}\underline{\theta}\phi(R)-\Delta(\underline{\theta}+\Delta)\right)W^2}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2},
$$

which certainly holds whenever

$$
\frac{1}{(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2}>\frac{\frac{1}{2}\underline{\theta}}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2}\Leftrightarrow
$$

$$
\begin{aligned}
(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2 &> \frac{1}{2}\underline{\theta}(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2 \quad\Leftrightarrow\\
\phi(R)^2(2\Delta^2+2\underline{\theta}\Delta+\underline{\theta}^2)+2\phi(R)&(2\Delta^3+2\underline{\theta}\Delta^2+2\underline{\theta}^2\Delta+\underline{\theta}^3)+\\
&+(2\Delta^4+2\Delta\underline{\theta}^3+\underline{\theta}^4)>0,
\end{aligned}
$$

which obviously holds. Since marginal costs are identical, this gives underinvestments in information acquisition of firms competing in a winner-take-all race with public signals.

(ii) First, we that $\widehat{R}(\sigma)$ is single-peaked in the revenue share. For a given R the equilibrium marginal revenue of information acquisition is maximized for the following revenue share:

$$
\hat{\sigma}^I(R)\equiv\frac{\widehat{MQ}(R)-2\widehat{MR}(R)}{2\left[\widehat{MQ}(R)-\widehat{MR}(R)\right]}=\frac{\underline{\theta}^2+(4\underline{\theta}+\phi(R))\Delta+3\Delta^2}{(\underline{\theta}+2\Delta)(2\underline{\theta}+\phi(R)+2\Delta)}
$$

Notice that for all R: $0<\hat{\sigma}^I(R)<1$, since

$$
(\underline{\theta}+2\Delta)(2\underline{\theta}+\phi(R)+2\Delta)-[\underline{\theta}^2+(4\underline{\theta}+\phi(R))\Delta+3\Delta^2]=(\underline{\theta}+\Delta)(\underline{\theta}+\phi(R)+\Delta)>0.
$$

This revenue share decreases in R, since:

$$\frac{d\hat{\sigma}^I(R)}{dR} = \phi'(R)\frac{\partial\hat{\sigma}^I(R)}{\partial\phi} = \frac{-\phi'(R)(\underline{\theta}+\Delta)^2}{(\underline{\theta}+2\Delta)(2\underline{\theta}+\phi(R)+2\Delta)^2} < 0.$$

Define $\hat{\sigma}^I_0 \equiv \hat{\sigma}^I(1)$ and $\hat{\sigma}^I_1 \equiv \hat{\sigma}^I(0)$. Hence for all $\sigma < \hat{\sigma}^I_0$ (resp. $\sigma > \hat{\sigma}^I_1$) marginal information acquisition revenues increase (resp. decrease) in σ for all R. Since marginal costs do not depend on the revenue share, we can conclude that for all $\sigma < \hat{\sigma}^I_0$ (resp. $\sigma > \hat{\sigma}^I_1$): $\hat{R}'(\sigma) > 0$ (resp. $\hat{R}'(\sigma) < 0$). Second, after substituting $\hat{\sigma}^I(R)$ in the marginal revenue function at the right hand side of expression (30), we obtain the following:

$$\begin{aligned}&(1-\hat{\sigma}^I(R))\left((1-\hat{\sigma}^I(R))\widehat{MPR}(R)+\hat{\sigma}^I(R)\widehat{MPQ}(R)\right)\\ = &\frac{\widehat{MPQ}(R)^2}{4\left[\widehat{MPQ}(R)-\widehat{MPR}(R)\right]} = \frac{p(1-R)\phi(R)W^2}{2(\underline{\theta}+2\Delta)(2\underline{\theta}+\phi(R)+2\Delta)}.\end{aligned}$$

We substract this expression from the efficient marginal revenues of information acquisition, as in the right hand side of expression (49), and obtain the following:

$$\begin{aligned}&\frac{p(1-R)\phi(R)^2W^2}{(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2} - \frac{p(1-R)\phi(R)W^2}{2(\underline{\theta}+2\Delta)(2\underline{\theta}+\phi(R)+2\Delta)}\\ = &\frac{p(1-R)\phi(R)W^2[\phi(R)^2+2\underline{\theta}\phi(R)-(\underline{\theta}+2\Delta)^2]}{2(\underline{\theta}+2\Delta)(\underline{\theta}+\phi(R)+2\Delta)^2(2\underline{\theta}+\phi(R)+2\Delta)},\end{aligned}$$

which exceeds zero if

$$\phi(R) > \sqrt{2(\underline{\theta}^2+2\underline{\theta}\Delta+2\Delta^2)} - \underline{\theta}.$$

Since $\phi(R)$ increases in R this inequality holds for all R if:

$$p\underline{\theta}+(1-p)\overline{\theta} > \sqrt{2(\underline{\theta}^2+2\underline{\theta}\Delta+2\Delta^2)},$$

which is stated in the proposition.

(iii) This part of the proposition follows directly from part (ii), and proposition 4 (i) and (iii), where $\hat{\sigma}^{II}_0 \equiv \min_R\{\hat{\sigma}(R), \hat{\sigma}^I_0\}$ and $\hat{\sigma}^{II}_1 \equiv \max_R\{\hat{\sigma}(R), \hat{\sigma}^I_1\}$. This completes the proof. $\square$

• **Proof of Proposition 8:** The first-order conditions for firm i's winner-take-all R&D investments change into:

$$
\begin{aligned}
\underline{\theta}\hat{R}_i^I(\underline{t}) &= W - \left(r_j \hat{R}_j^I(\underline{t}) + (1-r_j)\hat{R}_j^I(\bar{t};r_j) \right) \Delta, \\
(\underline{\theta} + \varphi(R_i))\, \hat{R}_i^I(\bar{t};R_i) &= W - \left(P^I(R_i,r_j)\hat{R}_j^I(\underline{t}) + [1-P^I(R_i,r_j)]\hat{R}_j^I(\bar{t};r_j) \right) \Delta,
\end{aligned}
$$

with $\varphi(.)$ as in (17), and $P^I(R_i,r_j) = \frac{p(1-R_i)r_j}{p(1-R_i)+1-p}$. Naturally the equilibrium R&D investments of revenue sharing firms equal: $\hat{R}_i^I(.|\sigma) = (1-\sigma)\hat{R}_i^I(.)$.

Firm i's expected profit of information acquisition given equilibrium R&D investments $\left(\hat{R}_i^I, \hat{R}_j^I\right)$ is summarized in the following expression:

$$
\begin{aligned}
&(1-pR_i)\pi_i \left(\hat{R}_i^I(\bar{t};R_i|\sigma), P^I\hat{R}_j^I(\underline{t}|\sigma) + (1-P^I)\hat{R}_j^I(\bar{t};r_j|\sigma); \left[\underline{\theta}+\varphi(R_i)\right]\sigma \right) + \\
&+pR_i\pi_i \left(\hat{R}_i^I(\underline{t}|\sigma), R_j\hat{R}_j^I(\underline{t}|\sigma) + (1-R_j)\hat{R}_j^I(\bar{t};r_j|\sigma); \left[\underline{\theta}\right]\sigma \right) - \frac{1}{2}\rho R_i^2, \qquad (50)
\end{aligned}
$$

where P^I stands for $P^I(R_i,R_j)$. Expression (35) gives the first-order condition for profit maximizing information acquisition, while the second-order condition is as follows:

$$
\rho \geq -(1-\sigma)^2 2p \frac{\partial \hat{R}_i^I(\bar{t};R)}{\partial R_i} \left(\hat{R}_i(\underline{t};R) - \hat{R}_i(\bar{t};R) + (1-pR)\varphi(R)\frac{\partial \hat{R}_i^I(\bar{t};R)}{\partial R_i} \right). \qquad (51)
$$

(i) We compare marginal revenues of information acquisition for public signals with those for private signals. Naturally, from (31) we obtain:

$$
\begin{aligned}
\widehat{MR}(R) &= \frac{\frac{1}{2}p\underline{\theta}\phi(R)^2W^2}{(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2} \\
&= \frac{\frac{1}{2}p\underline{\theta}(1-p)^2(\bar{\theta}-\underline{\theta})^2W^2}{[p(1-R)^2+1-p]^2(\underline{\theta}+\Delta)^2(\underline{\theta}+\phi(R)+\Delta)^2}. \qquad (52)
\end{aligned}
$$

Marginal information acquisition revenues in the winner-take-all race with private signals reduces to the following:

$$
\rho R = \frac{\frac{1}{2}p\underline{\theta}\varphi(R)^2W^2}{\Psi(R)^2} = \frac{\frac{1}{2}p\underline{\theta}(1-p)^2(\bar{\theta}-\underline{\theta})^2W^2}{(1-pR)^2\Psi(R)^2}. \qquad (53)
$$

When we compare denominators of (52) and (53), we obtain:

$$
\begin{aligned}
& [p(1-R)^2+1-p](\underline{\theta}+\Delta)(\underline{\theta}+\phi(R)+\Delta) - (1-pR)\Psi(R) \\
= \;& (E(\theta)+\Delta)[2\underline{\theta}+(1+R)\Delta] - pR(3-R)(\underline{\theta}+\Delta)^2.
\end{aligned}
$$

Since this expression is linear and decreasing in p it suffices to evaluate it for $p = 1$. For $p = 1$ the expression reduces to:

$$(1 - R)(\underline{\theta} + \Delta)[\underline{\theta} + (1 - R)(\underline{\theta} + \Delta)] \geq 0.$$

This implies that for any given precision R the marginal revenue of information acquisition in the winner-take-all race with public signals is smaller than the marginal revenue with private signals, while the marginal costs are equal. Hence, in equilibrium firms' invest more in acquiring private signals than in acquiring public signals.
(ii) From equations (35) and (53) we conclude that the marginal revenue of acquiring a private signal is decreasing in the revenue share σ. Since the marginal cost of information acquisition is unaffected by the revenue share, the equilibrium information acquisition investments are decreasing in the revenue share.
(iii) The first term of expression (36) is decreasing in σ, as shown in propositions 2 (iii) and in proposition 8 (ii). From proposition 4 it follows that there is a share $\hat{\sigma}^I < \frac{1}{2}$ such that the second term of expression (36) increases for all $\sigma < \hat{\sigma}^I$, and decreases for all $\sigma \geq \hat{\sigma}'$. Since both terms of expression (36) are negative for $\sigma \geq \hat{\sigma}^I$, $\hat{\Pi}'_i(\sigma) < 0$ for all $\sigma \geq \hat{\sigma}^I$. This completes the proof. $\square$

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